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ERGONOMICS, DESIGN AND RELIABILITY OF BODY ARMOUR

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ABSTRACT

The wearing of body amour has become a necessity for many professions and much work has gone into the optimisation of the mechanics of protection. In the present study a broader view of the effects of ergonomics, design, reliability and protection has been taken.

Three background topics are examined by reference to the literature. First, as an example of the threats and injury mechanisms that prevail in modern conflicts, the effects of blast injury to the head are investigated. This is followed by a review of ergonomic test methods and is completed by a study exploring the influence of history on modern body armour design.

Solutions to some of these problems are then considered. The problem of accurately measuring impact loads to the head is investigated and a rigid instrumented head form is demonstrated. This work showed that the filtering techniques derived from crash tests used in the current helmet standards are not applicable to ballistic impact events.

A one day wearer trial for police armour based on typical actions carried out by police officers in the performance of their normal duties is developed and demonstrated. A mechanical flexibility test is shown to give quantitative data but a direct link between ergonomic rankings and flexibility could not be established. Reliability of both soft and hard body armour is investigated and for typical armour types it is demonstrated that a minimal deterioration takes place with time and existing inspections techniques can highlight armour that is below standard.

This study has introduced measurement techniques in an attempt to quantify some of the effects investigated with the intention of using quantitative methods to improve armour design and minimise some of the negative effects of wearing body armour.

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List of Abbreviations

ACPO	Association of Chief Police Officers
AIS	Abbreviated Injury Score
ASTM	American Society for Testing and Materials
BC	Before Christ
BFD	Back Face Deformation
BS	British Standard
BSI	British Standards Institute
CAL	Caliber (of fragment)
CAN	Canada
CASPER	UK Casualty Reduction Analysis computer programme
CEN	Comité Européen de Normalisation
CDAT	Casualty Data Assessment Team
COST	European Cooperation in Science and Technology
DA-CMT	UK Defence Academy - College of Management and Technology
EOD	Explosive Ordinance De-mining
FE	Finite Element
FSP	Fragment Simulating Projectile
HG1A	HOSDB Handgun level 1A
HG1	HOSDB Handgun level 1
HG2	HOSDB Handgun level 2
HIC	Head Injury Criteria
HOSDB	Home Office Scientific Development Branch
HUMMVW	High Mobility Multi Purpose Wheeled Vehicle
IED	Improvised Explosive Device
IFW	Instrumented Falling Weight
ISO	International Standards Organization
KR1	HOSBD Knife Resistance Level 1
KR2	HOSBD Knife Resistance Level 2
MAHIS	UK Military Aircrew Helmet Impact Standard

MQT	Manufacturers Quality Test
NATO	North Atlantic Treaty Organization
Nij	Neck Injury Criteria
NIJ	National Institute of Justice
NPIA	National Police Improvement Agency
PAS	Product Approval Specification
PASGT	Personal Armour Systems for Ground Troops
PPE	Personal Protective Equipment
PPG	Physical Protection Group
PSDB	Police Scientific Development Branch
PTVF	Polyvinylidine fluoride
TBI	Traumatic Brain Injury
TRL	UK Transport Research Laboratory
SI	Severity Index
S1	PSDB knife identification code
STANAG	Standard Agreement
VBIED	Vehicle Borne Improvised Explosive Device
WSTC	Wayne State University Concussive Injury Score
UHMWP	Ultra High Molecular Weight Polyethylene
UK	United Kingdom
US	United States of America

List of Symbols

a	Acceleration
B	Bending rigidity
C	Bending length
F	Force
G (g)	Gravity
J	Joules
kG (kg)	Kilogram
kPa	KiloPascal
m	Metre
m	mass
mm	millimetre
ms^{-1}	Metres per second
ms	milliseconds
t	time seconds
UV	Ultra Violet light
V	Velocity
V_{05}	Velocity at which 5% of shots perforate and 95% stop
V_{50}	Velocity at which 50% of shots perforate and 50% stop
V_{95}	Velocity at which 95% of shots perforate and 5% stop
w	Weight per unit area
$\int$	Integral
$\sum$	sum

I dedicate this book to my Grandchildren

Jack, Alice and Alexander

With the hope they will always

“Boldly go where no man (or woman) has gone before”

(variation on the soundtrack to the theme from Star Trek)

Chapter 1. General Introduction

This study will examine specific areas relating to body armour development identified by the author after twenty years of study in the field as worthy of further investigation. Other researchers have investigated the performance levels of body armour against knife, spike and a variety of ballistic threats and much is already known about how to protect the body against these threats. Many standard methods of evaluating body armour to different performance levels have also been developed. However, there is still much that can be done to improve protective armour systems, in areas such as behind helmet trauma, ergonomics, reliability and flexibility. There is also a need to design relevant measurement methods for all of these factors.

The aim of this work is to examine some aspects of body amour that have not been extensively investigated by other researchers and attempt to optimise some of the parameters. This work will be multi-disciplinary and the specific areas investigated will include a case study of a specific threat i.e. blast to the head and possible novel measurement techniques. Other areas to be investigated are the effect of armour age on reliability, flexibility and the development of test methods for ergonomics. The measurements of forces, velocities and accelerations should help towards increasing the understanding of how the armour reacts.

There is anecdotal evidence that if armour is uncomfortable or makes an officer overheat when performing their duties it will not be worn. This is a particularly valid point at present as British troops are currently serving in extreme temperatures in Afghanistan. Even in Europe, summer temperatures can be high and Police and Security Forces find their armours uncomfortable. There is also a legal requirement for personal protective equipment to be issued in the workplace. Although public perception is that as much protection for the individual as possible should be worn, the most important factor is that the appropriate level of protection should be offered. At the lowest levels of protection the Health and Safety Regulations (1974) require that personal protective equipment (PPE) such as overalls, steel toe-capped shoes, hard hats and eye goggles must be provided in the work place. The amount of body protection to prevent sports injuries has also been increased wherever possible. Whereas 50 years ago pads for the legs were all that were necessary for cricketers, they now wear elbow pads, helmets and faceguards. Horse riders wear body armour and helmets and bicyclists wear helmets, knee and elbow pads. Body armour was not general issue for soldiers in the Second World War and fragment resistant body armour vests and helmets were first introduced for the military in the 1970's, with the Police introducing ballistic resistant body armour in the early 1990's.

As a case study of a typical injury threat chapter two reviews the published literature relating to the effect of trauma to the head resulting from blast and ballistic impact on helmets. How body armour interacts with the human body and its effect on the individual is becoming increasing important. Chapter two will also survey the published literature on the ergonomic problems posed by wearing body armour. Developing ergonomic trials to provide informative results should increase the knowledge base in this area and aid the development of a new generation of protective systems. There are a number of standard methods available to test body protection usually against specific threats. It is possible to certify armour against particular ammunitions, travelling at specific velocities and against knives and spikes of a pre-determined sharpness delivering a specific amount of energy. However, there are fewer standard methods that use a quantitative method to assess the ergonomic performance of armour.

Body armour has been used for centuries so is not a new topic and there have been many developments throughout the ages to overcome problems that are significant even today. Therefore, a historical review in Chapter three will investigate the influence of ancient technologies upon the development of current armour systems.

The ergonomics of body armour relate to the whole system and there are many specific areas that need improvement. To understand the problems of providing protection to specific areas of the body in more detail, Chapter four investigates protecting the head and alternative methods of measuring transmitted impact from blast as discussed in the case study in Chapter two. It is not possible to offer a high degree of either blast or ballistic protection of the head due to the weight that the head is able to bear without damage to the neck and spine. These limitations combined with the materials currently available, impose severe technical difficulties which have a profound effect on any helmet design to provide adequate protection. Modern ballistic helmets are known to provide penetration resistance against a variety of fragments and some ballistic threats.

The aim is to develop a ballistic test method that could be extrapolated to blast performance. An aluminium head form instrumented with piezo-electric transducers, film sensors and accelerometers was used to measure the impact forces applied to the head form by the back face deformation of helmets after ballistic impacts. The head form and an instrumented accelerated weight machine were also used to measure blunt impact forces applied to the helmet and the forces transmitted behind the helmet. Current test methods assess the absorption of the shock of the impact by measuring the acceleration to the head which is then compared with suitable head injury criteria (HIC). This test method was developed for use in the car crash industry where the transmitted speed of impact on the head is much slower. Current helmet test standards measure forces on the surface of the helmet and most helmets are tested for bump resistance. For the ballistic test the materials are formed into a helmet shell and a test to determine the ballistic limit velocity is carried out, where 50% of the shots penetrate and 50% are stopped within a $40ms^{-1}$ velocity spread. This method tells us the ballistic limit of the materials used for the helmet but nothing about what is happening to the head beneath.

There is no current standard available for assessing the ergonomics of Police body armour so part of this work has been to develop a standard method. The interactions of the human body with body armour are complex and methods to measure the ergonomic effects need to analyse the subjective responses in as objective a manner as possible. Chapter five describes the development of one day user trials based upon typical movements carried out by individuals as part of their military or police duties. The police trial was supported by the Physical Protection Group of the Metropolitan

Police (PPG) and the National Police Improvement Agency (NPIA). The user trial proved to be very successful and analysis of the work was presented by the author to the Association of Chief Police Officers (ACPO) and other Officers responsible for body armour at the NPIA in September 2008. Subsequently the methodology was presented to the European CEN-TC162-WG5-PG5 Body Armour Committee and they are currently considering adopting the method as part of their standard.

A complete armour panel is a composite lay up of many layers and often consists of several different types of material. The flexibility of the armour panel contributes to comfort to the wearer and it is not a property that can be assessed by any standard at present. Chapter 6 describes methods that could be used to measure flexibility. Small scale trials with a probe and a modified compression test were used to assess the stiffness of typical body armour materials. A large scale test was used to determine the stiffness of body armour panels and relate them to the ergonomics of the armours.
The flexibility of armour contributes to the comfort of the wearer and a method of measuring flexibility of armour panels has been developed as a comparative measurement for body armour

Two important further aspects of armour are the reliability of soft and hard body armour after time and these are examined in Chapter 7. The notion of determining the effect of damage that is not visible to the naked eye became an increasing concern and questions were raised about the effect of water damage to textile armour and crack damage in ceramic armour. In an investigation of textiles used in military armour systems, the effects on V_{50} performance of fragment impact on the textiles used in soft body armour are examined. The aim was to find if the ballistic properties of the non-water repellent textiles were degraded after contact with water. The systems used had been encapsulated in plastic covers and there was concern that the plastic could sustain damage that was not easily visible to the naked eye but would allow water ingress to the textile. A comparison of the ballistic properties of wet and dry panels was undertaken.

There was also a concern that older in-service ceramic armour plates may after time have sustained damage not visible to the eye. This study determines if there was any effect on ballistic properties from damage or deterioration due to age from samples selected from batches over a twelve year time period. Severe cracks were introduced into batches of plates, X-rays were then used to determine the positions of cracks and the ballistic performance of these cracked areas evaluated. A statistical analysis of both hard and soft armour results was performed in order to assess the V_{50} velocity and the velocity at which the failure probability was less than 5% (V_{05}) and their respective confidence limits.

The purpose of the following Chapters is to address the effects of armour design described above and expand the knowledge base in each of the areas with a view to optimising the effects of protection upon mobility.

Chapter 2 - Literature Review

Part 1. Case Study of Head Injury due to blast effects

2.1 Introduction

The emergence of Improvised Explosive Devices (IED's) as a major threat in current military operations in Iraq and Afghanistan has seen a significant change in injury patterns. Scott [1] reports that in military combat only 19% of casualties are caused by bullets and as high as 59% by fragments. Blast related injuries to the head (brain and ears) and blast fragmentation injuries to the limbs and face are seen more frequently in IED attacks with both personnel on the ground and those travelling in vehicles being targeted for this type of attack. The protection against penetrating injuries offered by body armour and helmets is significant and has increased the survivability of many casualties. However, helmets cannot completely protect the face, head, and neck, or prevent the kind of closed brain injuries often produced by blasts. The occurrence of Blast Induced Traumatic Brain injury (TBI) has been recognised and observed in significant numbers in US forces protected by body armour, with TBI being reported by Okie[2] in almost 60% of all blast victims. It is not yet clear whether this type of injury is a consequence of acceleration of the body by the blast or impact with the debris and the ground[3]. Makris[4]*et al* have measured the head accelerations in these events in full scale trials with instrumented dummies, however these trials are expensive and it would be useful to perform small laboratory scale trials replicating the forces and accelerations
seen in these events.

2.2 Blast loading

During an explosion the energy of the rapid chemical reactions result in hot gases being concentrated into a relative small volume, this causes the extreme high pressures known as the blast wave. This produces a spherical blast wave which rapidly expands until it dissipates into the surrounding space (the overpressure limit) then the front of the wave reduces in pressure in relation to the distance from the explosion. Therefore injuries from the blast wave alone are dependent upon the size of the explosion and how close to the explosion a person may be, Figure 2.1. Blast waves interact with objects in their path resulting in reflected waves increasing the magnitude of the following waves. If the blast wave reaches an interface between areas with differing properties part is reflected and part continues. In the human body this causes stresses to occur at the interface of tissues with differing densities such as the air/fluid interfaces of the lung which are particular vulnerable to damage by blast waves and produces the tissue damage referred to as blast lung. Ruptured ear drums are also a frequent injury of primary blast. The effect of reflections increasing the blast wave in the confined space of vehicles is known to increase the number of occurrences of blast lung injuries. Katz[5] reported 38% of the survivors in a Jerusalem bus bombing exhibited blast lung.

Figure 2.1. Blast explosion from a simulated mine *(after Makris* [3])

The movement of air displaced by the explosion, result in dynamic pressure known as the blast wind which follows an explosion. The blast wind accelerates bodies and causes injuries ranging from total body disruption, traumatic amputations to impact injuries from interactions with objects also accelerated by the blast wind.

The effects of blast injury on the human body are categorised into four main types. Primary blast injuries are the direct result of the pressures related to the shockwave produced by the blast, the blast or overpressure wave. This is a very fast event and effects organs of the body containing air, the lungs, bowel and ears. Secondary blast injuries occur when fragments from the explosive device or other objects thrown by the blast strike the victim. Small fragments such as shrapnel, nails, stones, soil and bone travelling at high velocities produce penetrating injuries on unprotected areas of the body and may cause behind armour blunt trauma on protected areas. Larger objects such as bricks cause contusions, fractures, concussion and traumatic amputations. Tertiary blast injuries are caused by the rapid accelerations as the body is thrown upwards by the blast and the resulting injuries from impacts with solid objects. Quaternary injuries cover the remaining injuries such as burns to the skin from the flash ball and toxicity from inhaling hot gases from the explosion.

Personal protective equipment supplied to military personnel is designed to protect the torso and head against the traditional threats of small fragments. Body armour vests are made from aramid fibres with ceramic plates provided for additional ballistic protection against high velocity bullets. The protective suit for Explosive Ordinance Disposal technicians (EOD) for de-mining and bomb disposal is the only PPE equipment that has been developed to offer protection against blast injuries. This suit is designed to offer complete protection to the whole body, except the hands but is too unwieldy for use in normal combat situations. However some of the EOD helmet technology developed for protection against blast could be used to increase the current levels of ballistic and fragment helmet protection.

Many researchers[2,3,5,6] have investigated the effects of blast on the human body to improve and develop the protective clothing provided for EOD and de-mining operations. Their work includes blast trials with protected and unprotected cadavers, hybrid III dummies, case studies[5] and also modelling the effect of blast. Typically the surrogates in the blast trials are placed at about 1 metre from the source of the blast which would be representative of the worst case for any personnel affected by a blast incident. Blast injuries from recent conflicts have also been reviewed with injury data being collated by degree of injury and parts of the body most affected.

2.3 Case studies of the effects of blast injury

As an example of the injuries sustained in primary, secondary and tertiary blast a case study by Mayorga [6] describes an incident in Iraq in which an EOD technician was exposed to primary, secondary and tertiary blast. Whilst the EOD technician was photographing the IED device prior to disarming it was remotely detonated and exploded. The victim was wearing a bomb disposal suit with helmet and face shield, he was thrown backwards 1.5 to 3 metres by the explosion. His rescuers reported he was barely conscious and that there were traumatic amputations to his fingers and he was bleeding from his nose and ears. He could not be transported inside the only available vehicle (a HUMMVW) so was placed on the bonnet (hood) with another soldier holding him in place. A second explosion occurred with the victim of the first explosion being thrown off the vehicle with his rescuer and the driver also now incurring injuries. Within a few minutes a third explosion took place thought to be from a secondary device buried below the second device which further injured these soldiers and a further three other soldiers who had gone to their aid. The head injuries sustained by the EOD technician included loss of consciousness and memory loss, injuries to the front and back (occipital) of the brain, face, eyes and eardrums.

Battlefield trauma surgeons Beaver and Schenarts [7] members of a US reservist surgical team serving in the 933rd forward surgical team at the 67th combat support hospital in Iraq in 2004 observed that blast injury from mines and IED's were the major causes of injury treated in their unit. The very small fragments from IED's could penetrate deep into the body and that often the small size of the entrance wounds bore little relationship to the internal injuries they found. Gawande's [8] preliminary account in 2004 on the US casualties of the Iraq war reported the combination of injuries, penetrating, blunt and burns seen in IED's made them difficult to manage. Victims of IED attacks often have so many small wounds they can die of blood loss before their major wounds are treated. He also noted that IED's were causing blast injuries that extend upward under armour. He also highlighted that a high number of blinding eye injuries were being treated. The soldiers had been issued with and directed to wear eye protection but due to the ugly appearance of the goggles had not been wearing them. This unexpected problem has led to the introduction of a new more fashionable design of goggles which the troops were happy to wear and this had significantly decreased the number of eye injuries treated.

2.4 Blast loading and vulnerability of the head to injury

The severity of injuries reported in 828 servicemen injured by blast from terrorist explosive devices from 1970-1984 was reviewed by Mellor[9] who attempted to relate the patterns of injury caused by the explosions to the blast loading. Accurate forensic data was available for each of the cases he reviewed due to the nature of the conflict in Northern Ireland at the time. Mellor classified the victims into 4 groups Table 2.1 according to the level of blast loading they had sustained and related the cause of death to these blast classifications, Table 2.2. Mellor found that the 90% of servicemen killed or injured were wearing body armour but less than 20% were wearing helmets.

Head injury was the second most important cause of death, it was the primary cause of 25 deaths and a contributory factor in a further 128 deaths. Only 5 servicemen with severe head injuries survived long enough to receive treatment and only 1 of these recovered. There were 113 servicemen with less severe head injuries and of these 7 were left with some damage to their central nervous system directly as a result of their injuries. Perforated eardrums were seen in 288 survivors with 137 experiencing permanent hearing loss as a result.

Table 2.1 Victim groups according to Blast loading (from Mellor) [9]

Group	Overpressure (kPa)	Level of Blast loading overpressure	Classification
1	<150	Rupture ear drums	Minor
2	150-350	Higher than group 1- but no primary lung damage	Moderate
3	350-550	Primary lung damage	Severe
4	>550	Severe primary lung damage with a significant increase in deaths	Very Severe

Table 2.2 Cause of death related to estimated blast in 216 servicemen from (Mellor) [9]

	Group Classification (from table 1)			
	1	2	3	4
Number of patients	5	28	38	145
Cause of death as % of patient numbers within groups				
Total body disruption	0	14%	10%	16%
Head injury only	40%	29%	16%	7%
Head and chest injury	0	21%	26%	21%
Secondary missile injury with head and/ or chest injury	0	36%	47%	40%
Severe chest injury alone	0	0	0	17%
Other	60%	0	0	0

Mellor concluded that from 1970 to 1984 those close enough to an explosion to suffer severe traumatic amputations were unlikely to survive the effects of the blast wave. For the cases where head injury was the cause of death it was observed that deaths may have been caused by brain haemorrhages caused by the blast wave or motion of the brain within the skull. The majority of victims showed evidence of external injuries to the head caused by falling debris or contact with a surface when the victim was thrown by the blast. It should be noted that the high incidence of external head injuries causing death where the blast loading overpressure was low (minor) may also be affected by the fact that only 20% of the victims wore helmet protection.

A casualty review of 143 US soldiers who received treatment for fragment or bullet wounds at US Seventh Army hospitals during Operation Desert Storm (February 20 to March 10, 1991) was undertaken by Carey [10]. At this time all soldiers were wearing protective body armour and helmets. Only 5% of the wounds recorded were by bullets, fragmentation accounted for 95% of the wounds treated, 17.3% of these were head wounds (24 soldiers) with 7 of these soldiers receiving a head wound alone. The location of these head wounds were eye-8, face-7, forehead-4, suboccipital-1, temporal 1 and 3 unknown. A further 4.3% sustained neck wounds. Only two brain wounds were treated (1.4%) with the entry wound being below the area of the skull protected by the helmet. Three untreatable brain wounded soldiers received by the forward hospitals were not included in this review. Cary[10] concluded that in Operation Desert Storm the percentage of head, neck and face wounds were approximately the same as those seen in WWII and Korea.

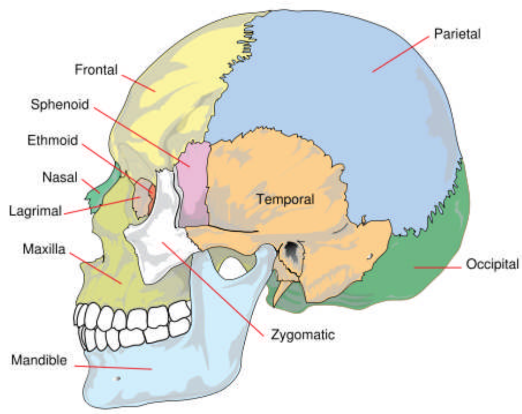

Figure 2.2 Locations of human cranial bones

Operation Desert Storm was of short duration, Carey[10] surveyed wounded hospital casualties and at the time of writing he did not have a complete data set of fatalities so his review should be considered as a ‘snapshot’ of injury. He also reported that his survey was comparable to the observations made by Uhorchak[11] and the US

Army's casualty data assessment team (CDAT) who evaluated 204 wounded soldiers evacuated to US military hospitals in Germany. They included rear area personnel wounded by a rocket attack by Scud missile and again found that 90% of the casualties were wounded by fragments with the head and neck accounting for 13% of the wounds. The survey was by soldier interview so complete forensic data was limited.

In a similar survey to Mellor[9], Lewis[12,13] reported that blast related injury accounted for 35% of the deaths in UK operations in Iraq during 2003 to 2007 and 28% of the deaths in Afghanistan between 2001 and 2007. With 57% of these deaths attributed to roadside IED's and a further 12% were attributed to vehicle borne IED's (VBIED). Only 4% of the deaths were attributed to primary blast alone, 31% were a combination of primary and secondary blast, 34% were from secondary blast with tertiary blast accounting for the remaining 31%. The entry wound sites of the fatal secondary fragmentation injuries were mapped and these were found to be mainly to the head, neck, face, arm and underarm. Most military personnel at his time would have worn body armour and ballistic helmets and the majority of the 34% of the injuries being to areas of the head unprotected by the helmet such as the face and neck. This is in agreement with Carey[9] and although there have been major improvements in patient care in recent years the vulnerability of the head to fragment impact is still evident.

A study by Godusky[14] evaluated battle injuries sustained by the 1st Light armoured reconnaissance battalion in Iraq. During March to August 2004, there were 32 attacks which wounded 120 Marines causing 188 injuries, 95% of these injuries were from IED or mines. The majority 70% were head injuries and wounds to the upper body, whereas lower extremity injuries (11%) were as expected, given the threat and the body areas exposed. He noted that 23% had ear injury which was the most common single injury type. Ballistic body armour and eye protection was worn and he concluded that this reduced the number of injuries to these protected areas. Walter Reed Army Medical Center screened 155 patients who had returned from Iraq between July and November 2003 and were thought to be at risk for brain injury. Of the 88 blast cases 61% were identified as having sustained a brain injury. Difficulties experienced as a result of a closed-head blast injury include post concussion complaints such as decreased memory and attention/concentration, headaches, slower thinking, irritability, and/or depression. Smith [15] reported a study by Hill[16] who had recorded injury data from 5600 blast incidents that resulted in 495 fatalities. Brain injury was seen in 66% of these 495 fatalities and 49% had skull fracture injuries that could be linked to injuries indicating impacts with a solid surface or an object. The remaining 17% of brain injuries showed no skull fractures suggesting they were caused by inertial acceleration of the brain.

To investigate this Smith performed 23 blast trials with three different explosive charge weights (2kg, 4kg and 8kg) and measured the peak head acceleration of protected and unprotected Hybrid III dummies [17] as they impacted onto a steel plate, Table 2.3. In the unprotected trials Smith found that a 314 kPa pressure wave generated a blast acceleration of 292g to the head. Smith considered this to be well within the range of serious closed head injury and that impact with the steel plate was likely to be fatal. Smith also manually pushed unprotected dummies onto the steel plates to give a non-blast acceleration value. Smith measured a head acceleration of 386g in the manual test on an unprotected dummy and concluded that this was similar to the acceleration the head might experience whilst being blown backwards by a blast. He also showed that for the protected dummy wearing an EOD protective helmet, the mean blast acceleration to the head was greatly reduced for all charge weights.

Table 2.3 Measurement of head accelerations during blast *(after Smith)*[15]

Condition	Charge weight kG	Mean Peak pressure (kPa)	Mean Duration (ms)	Mean Peak Head acceleration (g)
Unprotected	2	165	1.34	166
	4	314	1.18	292
Protected	2	154	1.16	16
	4	273	1.02	34
Impact onto a steel plate	8	424	0.5	80
Unprotected manual pushover test				386
Protected manual pushover onto a steel plate				65
				67

2.5 Mechanisms causing Brain injuries

When the head hits an object the skull can be fractured and cause damage to the brain known as an “open” brain injury, Galloway[18] reported the force required to fracture the different bones of the head this is reproduced in Table 2.4 and shows that temporal and parietal bones are weaker than frontal and occipital bones.

Table 2.4 Penetrating Forces for Skull fracture *(after* Galloway)[18]

Cranial Vault Location	Penetration Force (kN)
Frontal bone	2.74 - 8
Parietal bone	1.76 – 4.9
Temporal bone	1.67 – 1.86
Occipital	5.14 – 9.54

Sarron’s[19] 2004 paper concluded that intracranial pressure measurement could accurately predicted the risk of injury. Ballistic helmets offer some resistance to penetrating head injury but are not able to protect against some “closed” brain injuries which are caused by different mechanisms.

Extreme linear acceleration/deceleration of the head caused by impacts which force the brain to move back and forth across the inside of the skull is known as coup/contrecoup injury, Figure 2.3. This can cause shear stresses in brain tissue and can cause “closed” brain injuries which can occur when there is no apparent skull fracture. The result of the reflected stress wave set up in the head are contusions where a coup/contrecoup injury can occur either at the site of impact or on the opposite side of the brain from the impact. Rotational forces during impact can also cause contusions in the brainstem[20].

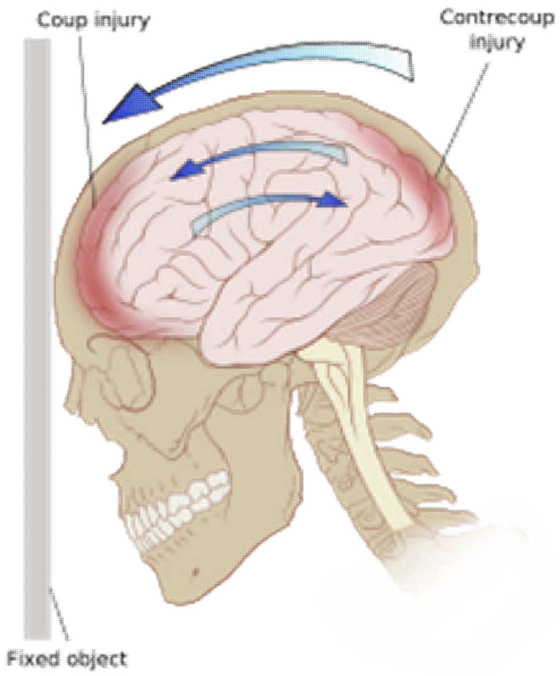

Figure 2.3 Mechanism of coup/contrecoup head injury

The kinetic energy of a blast wave can also be transferred through the central nervous system to the brain tissue (vasculature) of the brain causing diffuse damage to the nerve fibres (axons). The common types of brain injury mechanisms have been identified by Melvin and Lighthall[21], Table 2.5.

Table 2.5 Brain Injury Mechanisms (after Melvin and Lighthall) [21]

Skull deformation/fracture
Contusions caused by movement of the brain against the interior of the skull
Infarction or pressure
Contrecoup (at the opposite side of the impact point)
Motion of the brains hemispheres relative to the skull and each other
Rupture of the bridging vessels

The classification of injury and its correlation to the Abbreviated Injury Score (AIS) as recommended by Ommaya[22] has been generally accepted by Medical and Scientific Community as a guide to grading concussive injuries and this is reproduced in Table 2.6. These definitions have been used in the determination of tolerance levels for head/brain injuries.

Table 2.6. Grading of concussive brain injuries (after Ommaya)[22]

AIS level	Clinical description	Pathological description	Outcome (1 month)
1	Stunned without amnesia. Minor symptoms e.g. Headaches and dizziness	Not known, CT and MRI scans normal, skull fractures and intracranial bleeding uncommon	Normal unless a post concussive syndrome developes
2	Amnesia without coma Type A: slow onset Type B: immediate onset		
3	Coma<6hours Includes classic cerebral concussion, minor and moderate head injuries	Increasing numbers of diffuse lesions and/or intracranial bleeding and blood clots CT and MRI scans usually	Morbidity increasing to 35% +
4	Coma 6-24 hours Severe head injuries	abnormal; 20-50% incidence of skull fracture	and mortality to 50%
5	Coma >24hours Severe head injuries		
6	Coma/death within 24 hours fatal head injuries		

Mellor[23] evaluated 253 head/neck injury case results from a European Collaborative research program (COST 327) for the Transport Research Laboratory (TRL). He found that 67% had head and 27% neck injuries, with rotational motion causing 60% of the AIS2 and above injuries and linear motion 30%. During the accident 12.9% of the cyclists lost their helmets. They concluded that if the energy absorption of the helmets could be improved by 24% it would reduce by 20% the AIS 5 - 6 casualties to AIS 2-4.

2.6 Review of Injury criteria

Apart from the work on blast for EOD applications, the majority of research into the impact tolerance of the head, neck and brain has been carried out by the vehicle safety organisations for the design of protection from impact in vehicle collisions and those studying head impacts for sports medicine. Instrumented anthropomorphic mannequins usually Hybrid III [17] have been used to measure impact forces and accelerations in impact situations. The major research groups studying head/brain injury tolerances have validated their data from these surrogates by measurements taken from skull fracture and tissue damage using cadavers. Whilst there are limitations of using cadavers as their response are not quite the same as living tissues the force, acceleration, velocity, and time measurements provide guidance when calibrating the responses from hybrid III dummies and for finite element (FE) modelling. The research in these areas has resulted in injury criteria which will be discussed below being developed for crash and impact events. These impacts impart energy over a longer time period than blast impact and consequently the injury criteria for the head is being re-examined by several groups investigating EOD protection as to its suitability for assessing blast injury.

2.6.1 The Wayne State University Concussive Tolerance Curve (WSTC)

This has been used for the past fifty years and is the foundation for most currently accepted head injury indices and it relates the linear acceleration of the skull (y-axis) and impulse time (x-axis) needed to produce skull fracture. Short pulses of high acceleration can produce injury and lower accelerations require longer pulses to produce injury. The curve was based on impacts on embalmed cadavers by Evans and Lissner[24]. Following on from this work Gadd[25] proposed plotting the injury curve on a log-log scale to achieve a straight tolerance line to obtain a severity index (SI).

The slope of Gadd's log-log plot was 2.5 which became his power weighting factor and that if SI exceeded 1000, there was a threat to life.

$$SI = \int [a(t)]^{2.5} dt$$

Where: SI = Severity Index

a = acceleration

t = time Equation 2.1

The major criticism of the work is that it was based on a limited sample size of cadavers and at 1-6ms the time period of the impacts as being too short for crash simulation applications. However, for ballistic and blast work the short time period is valid as these are very fast events. Subsequently for crash simulations it has been replaced by the Head Impact Criteria (HIC) described below.

2.6.2 Head Injury Criterion (HIC)

Head Injury Criteria (HIC) was developed for use in crash tests with instrumented anthropomorphic dummies by Versace[26] whose formula includes the peak acceleration, duration of the pulse and shape of the acceleration signal. The linear acceleration experienced by the head a(t) is integrated over a time period (t_2 - t_1).

$$\text{HIC} = \max \left\{ (t_2 - t_1) \left[\frac{1}{(t_2 - t_1)} \int_{t1}^{t2} a(t) dt \right]^{2.5} \right\}$$

Where: HIC = Head Impact Criteria

a = acceleration

t = time Equation 2.2

For vehicle crash situations the derivation of maximum HIC during the time period, $t_2 - t_1$ is limited to 36ms. These time limits are selected from the signal by identifying the first and last peaks of acceleration that exceed 40g. Backaitis [27] and Eppinger [28] interpreted HIC as a measure of the rate of change of kinetic energy imparted to the head. Prasad and Mertz [29] recommended HIC duration be limited to 15ms or less (HIC_{15}) and they developed a set of probability curves linking HIC to the AIS system of analysing head injury. They calculated that an HIC value of 1000 represented a 16% risk of AIS 4 or greater brain injury. The HIC value of 1000 is used by the US Department of Transportation in crash protection tests as the concussive threshold for impacts to an unprotected head. The Severity Index SI value of 1500 is used in the US by the National Operating Committee on Standards for Athletic Equipment, as the concussive threshold for helmeted head impacts.

In physical terms, HIC predicts that large accelerations may be tolerated by the head for short times. The time duration used for the HIC calculation is typically 5-15ms and the amount of data available for less than 1ms [30] is very limited. Also a 1650Hz low pass digital filter is applied to the raw data used for calculating HIC data although this filter 'smooths' the signal and makes it easier to interpret it restricts any frequency higher than 1650Hz, reducing peak acceleration values. These limitations have lead many researchers in the field to question the applicability of HIC to IED high rate blast head trauma as the acceleration effects of near field blasts are often shorter than 5ms.

To improve and develop predictive FE analyses, protected (Med-Eng EOD prototype suit) and unprotected instrumented anthropomorphic dummies were used by Dionne et al[31] to assess the validity of HIC for impacts to the head from the initial and reflected blast wave. The study found that average head acceleration was best suited to calculating HIC for head injury assessment. The use of HIC for the protected cases gave similar outputs to those seen in car crash situations or impacts with the ground and concluded that HIC would be suitable for use for the well-protected case.

For the unprotected case they considered that HIC was not appropriate for assessing injury. The durations of the acceleration signals were less than 5ms which is a third (0.3) of the time period recommended by Prasard and Mertz[29] and a seventh (0.14) of the time period used in vehicle crash safety tests. The extremely fast speed of the event resulted in a very sharp peak acceleration which meant that HIC values were influenced by the filtering frequency chosen to process the signal. They recommended that this should be investigated by improving the limits of integration of the time interval and proposed using a velocity curve rather than the acceleration curve. This was in agreement with work by Bass et al[32] who also found in his study with cadaveric specimens that the HIC was not a good predictor for head injury. Bass duplicated the instrumentation setup used for the Hybrid III test head and neck form in his cadaver study and found for all fracture tests, that the forces required to cause a fracture were all well below the HIC value. Dionne *et al* [33] had already investigated a new HIC impulse relationship for blast to show a proposed linear relationship between the predicted blast impulse and HIC values calculated from the acceleration signals. The 2002 linear relationship was not based on physical principles but by 2006 Dionne *et al* [34] had improved the model for the head and introduced physical considerations. Applying various mathematical derivations he then calculated a new probability of survival curve based on the total probabilities of AIS 5 and AIS 6 as a function of the HIC. From these curves Dionne abstracted the HIC values corresponding to the survivability levels, table 2.7.

Table 2.7 HIC corresponding to survivability levels (after Dionne[34])

HIC value	Survivability %
809	99
1346	90
1848	50
2355	10
2910	1

The HIC values in Table 2.7 were used to generate a blast induced injury chart based on explosive charge and standoff distance in terms of probability of survival. Dionne [34] constructed a combined head/chest blast injury chart of head acceleration/chest overpressure, related to charge weight and standoff distance for both the protected and unprotected cases. Proposed injury tolerances of the main impact and non impact models were also summarised by Anctil[35]. They have been in use for many years and were developed for impact applications other than blast. Although they could be used as predictive models it is only recently that there has been further development of the HIC for blast loading by Dionne *et al*[31].

2.7 Neck injury criteria

If damage to the neck is not caused directly by fragment impact during the blast event, neck injuries can occur from a dynamic impulse transmitted to the neck by the difference in the rates of acceleration of the head in relation to that of the chest. Bass *et al* [30] have reported that as this transmitted force is delayed in time it is relatively slow in comparison to rate of impact of the blast wave and has concluded that these injuries can be compared in rate to those seen in typical car accidents.

Bass *et al* [30] recommends that two existing criteria are appropriate for the neck. For the upper neck, the Neck injury criteria (Nij) proposed by Mertz [36] which is the US Department of Transport [37] criterion for hybrid III dummies. This assigns an injury reference value of 1 to a 30% risk of severe neck injury. Based on the peak flexure and tension limits from cadaver and human volunteer tests, the proposed peak tensile force limit was 3.3kN. Time versus tension was determined from Hybrid III crash tests with the duration of the time period (greater than 45ms) based on the muscle strength of human volunteers. Mertz also proposed a compressive neck tolerance limit of 4kN reducing to 1.1kN if the duration of the loading was greater than 30ms, based on work with Hybrid III dummies replicating sports injuries.

For lower neck injuries Bass[38] has developed a criteria based on lower neck force and moment values from studies on cadaveric specimens. Both criteria allow for the effect of loading the neck in tension/compression and flexion/extension moments. Bass accepts that the hybrid III dummy neck is not particularly biofidelic in bending but this is less important in blast where this motion is not expected to be a dominant factor in the injury mechanism.

2.8 Effect of helmets

Despite reporting the limitations of HIC, a study by Bass *et al* [30] used HIC to evaluate the blast effects from two simulated IEDs of different charge weights of C-4 on helmet frontal area/helmet mass of four EOD helmet designs. The simulated IEDs were suspended 77cm (+/-0.1cm) above a reference point on the floor of the apparatus 64cm (+/-0.1cm) from the chest and 59.5cm (+/-0.1cm) from the nose. As the acceleration of a head/helmet during blast loading is directly related to the area of the head exposed to the blast, and the force to accelerate the head/helmet is inversely related to the mass of the head/helmet. Bass *et al* used this ratio and normalised the helmet area/mass of their designs against the frontal area and mass of the Hybrid III dummy head/neck complex which was the same in all tests enabling them to compare the HIC values of each design.

Bass *et al* found that a larger helmet/visor frontal area provided a greater area for the momentum of the blast to be transmitted to the head. However, the additional mass of a larger helmet increases the inertia of the helmet effectively reducing acceleration which delays and reduces the peak force to the neck, Figure 2.4. Bass *et al* were investigating EOD helmets which are heavier than normal ballistic helmets. So although the results can be interpreted as an indicative trend for helmet designs, ergonomically increasing the mass of the combat helmet is not desirable

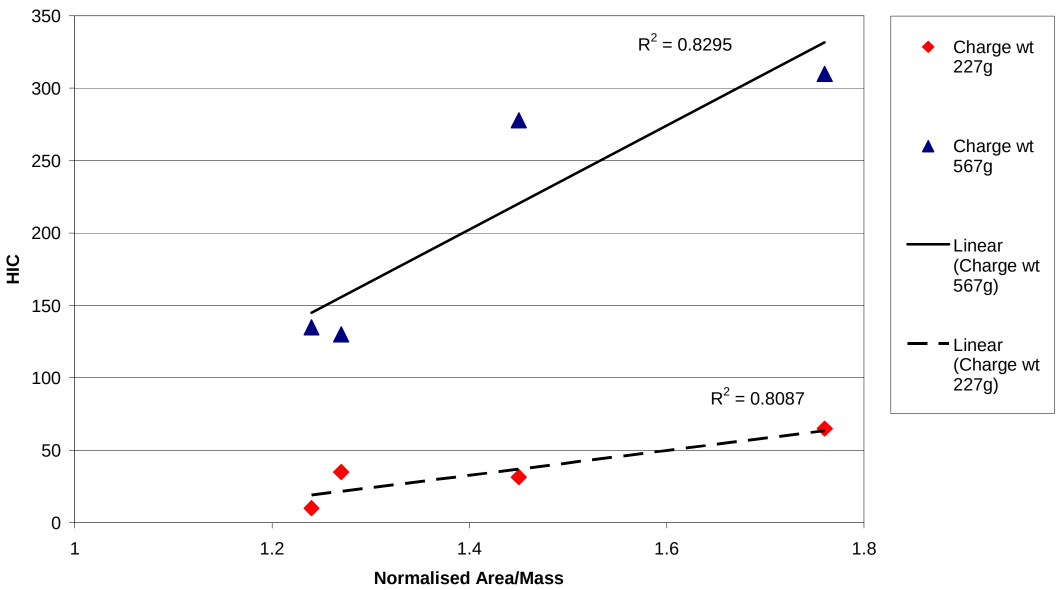

Figure 2.4 Variation in HIC with helmet frontal area/helmet mass for EOD helmets with IEDs of 227g and 567g, after Bass et al [30]

An earlier study of different lightweight helmet systems by Makris and Bass *et al*[39] reported that a full face visor would aerodynamically deflect the blast wave so that a full face visor mounted on a stable helmet provided significant protection against blast. This study also used HIC_{15} and Prasad/Mertz[29] injury criteria (M-AIS) to assess the effects of blast loading from anti-personnel mines against Hybrid III dummies fitted with and without US Military PASGT helmets and goggles, Figure 2.5. The set of curves developed by Prasad/Mertz[29] equates an HIC of 1000 with a 16% probability of a severe (AIS4) head injury, a 55% probability of a serious (AIS3) head injury and a 90% probability of a moderate (AIS2) head injury.

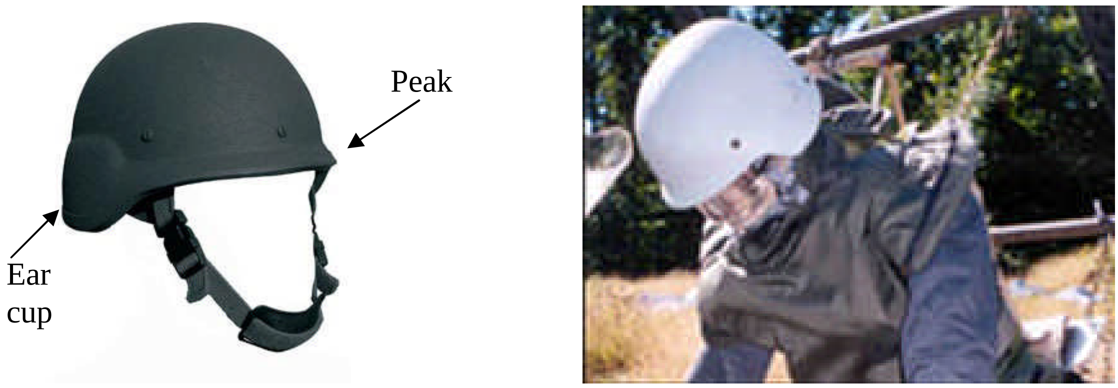

Figure 2.5 PASGT helmet showing peak, ear cup shape and fitted with goggles to Hybrid III dummy for blast tests, after Makris and Bass [39]

Blasts from mines containing as little as 100g C4 caused PASGT-style helmet and goggles, (no visor) to be ejected from the mannequin's head. The study also found that there was a high probability of head injury when the military helmet was worn without a visor and that the flared out ear cups created a larger profile to interact with and trap the blast. This resulted in higher head accelerations, well above the 300g limit recommended by MAHIS[40]. The HIC_{15} values were high enough to indicate a 100% probability of a fatal head injury.

2.9 Review of Helmet Standards

Many of the current helmet standards are designed to evaluate head protection against low energy impacts e.g. police riot (PAS017:1995[41], CAN/CSA-Z611-M86[42], NIJ Standard-0104.02[43]), motorcycle and vehicles (BS6658:1985 [44]) and sports helmets (ASTM F513-89[45], ASTM:F910-86[46]. These helmet standards which are briefly reviewed below, do assess blunt trauma but since the impacts are of longer duration than ballistic or blast impact, can only offer limited guidance as to the performance of behind armour blunt trauma of a helmet.

UK Military combat helmets are tested for ballistic resistance from penetration against fragments and bullets to UK/SC/5449[47]. They are also required to meet the shock absorption test described in UK/SC/6108[48]. The apparatus and test method described in BS6658:1985[44], paragraph 6.2.1 is used, Figure 2.6

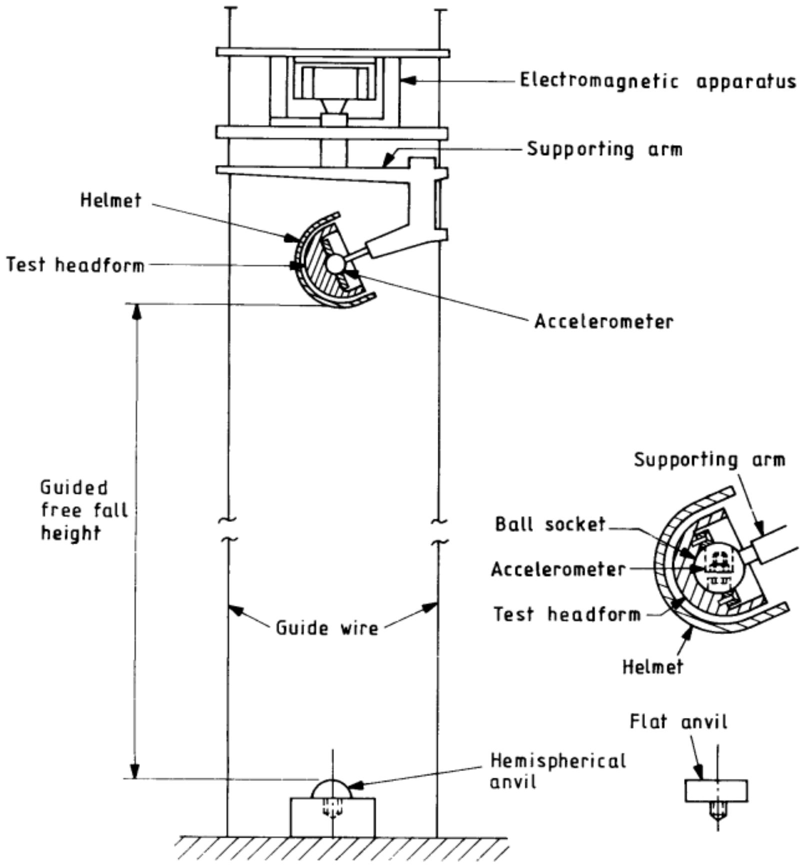

Figure 2.6 Typical drop test set up (after BS BS6658:1985[44])

This is a drop test which requires a helmeted head form instrumented with an accelerometer to fall at 6.5ms^{-1} and impact onto a flat anvil. The maximum deceleration of the head form measured by the accelerometer must not exceed 400g to pass. This peak acceleration value of 400g is also used by the US Army[49] as the survivable limit when evaluating aircrew protective headgear. The current UK Military Aircrew Helmet Impact Standard (MAHIS)[50]. follows the exact test method for shock attenuation and penetration resistance described in BS6658:1985[44] which require that the maximum deceleration of the head form should not exceed 300g[51].

The blast study by Makris and Bass[39] measured 799g for a head form fitted with the PASGT helmet and 754g without a helmet over a time period of less than 15ms highlighting a difference in the rates of loading of the standard test and a blast event. The currently accepted standard values of 400g and 300g for military helmets may mean the test standards described above are not appropriate for the evaluation of the performance of combat helmets under blast conditions.

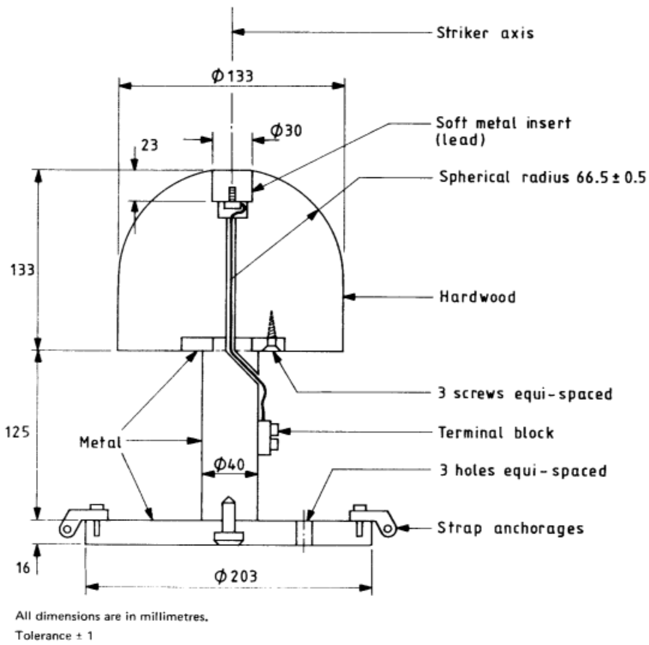

Figure 2.7 Typical penetration resistance test set up (after BS BS6658:1985[44])

The penetration resistance of a helmet is assessed by dropping a 3kg conical spike striker from either 2 or 3 metres onto a helmet supported by a wooden head form. A soft lead plug is used as a backing material to ensure electrical contact under the impact area, as illustrated in Figure 2.7. The striker should not make electrical contact with the head form. Similar versions of the BS BS6658:1985[44] head drop impact test methods are internationally used for most protective helmet standards(41,42,43,45,46) as a simple straightforward method of assessing the bump and penetration resistance of helmets. These Standard helmet test methods have been designed for and are appropriate for assessing low velocity impacts, such as car or motorcycle crashes or sports injuries. They continue to offer good data for vehicle collisions, bumps and falls. However the major limitations of these standard tests are their loading rates, they are all low-velocity gravity drops imparting energy to the helmets at a slower rate than would be expected in a ballistic or blast situation. For instance in their blast trials on US military helmets Makris and Bass [39] have measured twice the amount of acceleration than is accepted for these standards. There is currently no standard test available that would evaluate these loads.

Part 2. Review of Ergonomic Factors of Body Amour

2.10 Introduction

In the past twenty years most of the research into body armour has been focussed on defining the threat level[52] so that the correct level of ballistic and knife protection is worn, also in reducing bulk and weight and developing more flexible armour systems. Consequently many body armour solutions are available for a variety of specific threat levels. However, there is less information in the Police sector about what effect wearing armour has on human performance. Recently the interest in the human factors, (ergonomic) aspects of body armour has increased and ergonomics have become an important factor to consider in the design of new armour systems. Parsons [53] recommends the best way to find out if a person is comfortable is simply to ask them and this makes perfect sense. However this data will be purely subjective, so to obtain quantitative data from ergonomics tests depends on asking the right questions and designing a valid set of experiments. Weimar[54] recommends that when designing an experimental study to assess and predict human response the study should be designed to be as near as possible to the real situation. A critical question is the sample size, if it too small insufficient information restricts the accuracy of the results and if the sample size is large the study may be too time consuming and expensive.

2.11 Ergonomic studies

The majority of ergonomic studies into balancing the effect of wearing body armour protection against mobility and comfort have been carried out for military wearers of body armours. Poorly fitting armours with the weight distribution over the body being ‘unbalanced’ can cause chafing. Such armour may also interfere with and effect the operation of other equipment that is carried on the body. This can affect the performance during their normal duties, resulting in discomfort which increases irritability and leads to exhaustion, Ashby [55]. The trials described below provide some useful information about specific armour systems and tasks but are all non-standard and therefore one trial cannot be compared objectively with another.

Scott[56] reports that wearing a ballistic helmet can reduce casualties by up to 19%, wearing body armour alone by 40% and wearing both can reduce casualties by up to 65%. Couldrick[57] used a casualty reduction analysis simulation (CASPER) and demonstrated the effect of reduced casualty numbers by increasing coverage such as arm protection, collars and groin guards. However, he concluded that although extra coverage was beneficial in reducing casualties that increasing protection was a ‘trade–off’ against mobility which may also have an effect on casualty numbers.

In troop trials Lotens [58] compared wearing sportswear with wearing body armour and reported that there was 7% degradation in performance for body armour and 1.5% for wearing helmets. Ashby *et al*[55] also used troop trials in a four day study to compare the degradation in human performance by measuring the reduction in speed of the subjects to complete an assault course whilst wearing six different armours.

They had chosen to design their own trials and had rejected the use of ISO/FDIS 14876-1 (2002)[59] Standard as having little relevance to military tasks. Although there is a North Atlantic Treaty Organisation (NATO) standardization agreement (STANAG No 2138) which offers advice on troop trials [60] this also was of little help as it does not recommend any specific movements to assess the armours. As expected they found that increasing the amount of armour worn, reduced the speed of the subjects to complete the course.

Zamir [61] did use the ISO/FDIS 14876-1 (2002)[59] standard to assess the ergonomics of a conventional body armour where the weight is carried mainly on the shoulders. This was compared with a novel design which transferred the weight to a waist belt. The procedure described in section 2.3 below was followed. However, the results were confusing in that he reported better results for his heavier plates. This is counter intuitive and he attributed it to the performance allowance factors in the standard. He had a protection allowance factor of 2.1 for his light ballistic plates and 2.6 for his heavy ballistic plates and these factors may not be exact enough to differentiate between the armour effects. He rejects this standard due to its analysis in a second piece of work in 2006[62] and chooses to design a trial with heavyweight vests based on typical movements of a soldier e.g. running, leopard crawl and firing exercises. He analysed the data using a statistical package based on their perceived comfort or discomfort. Couldrick and Iremonger[63] also commented that prEN CEN ISO14876-1 (1999)[64] was very subjective and that the terms used in the questions were not precise between levels. Also that some of the exercises chosen may not relate to typical actions carried out by the users.

Keorhuis [65] also designed a study based on typical military manoeuvres and as Ashby had chosen to measure the reduction in speed to complete tasks to evaluate armour. He concluded that as the weight of armour increased the speed to complete a task increased. He also measured heart rate whilst performing the tasks with and without armour and found that there was no appreciable difference in heart rates whilst wearing body armour. Kistemaker [66] chose to measure skin and rectal temperature to assess the ergonomic effects of thermal strain whilst wearing bomb disposal suits (EOD). The exercise was walking under laboratory conditions using treadmills. Whilst for this application measuring the burden of thermal strain using rectal temperature is relevant it is an invasive procedure and it would not be easy to use this method for the general assessment of body armour. Kistemaker [67] continued this work and found that for a sit on the floor and reach toes test, reach was restricted by 49% whilst wearing EOD. For standing and reaching there was a 25% reduction in reach.

Full body protection for a soldier against improvised explosive devices (IED's) covering the head, body, legs and arms was investigated by Bruno[68]. He used a 500 metre obstacle course and exercises such as running, aim and fire and swinging arms. He measured the time taken for soldiers to complete the course and had the soldiers fill out a simple questionnaire which scored the armours from poor to excellent. He found that wearing the complete assembly resulted in a 34% increase in time to complete the tasks. Blake Mitchell[69] evaluated the size and fit of armour for 139 females over a two week period, by arm movements and typical tasks such as throwing a grenade, combat roll, simulating aiming a weapon, climbing a ladder, stepping and jogging. The subjects were asked to evaluate the armours for overall fit, overall comfort, comfort due to the back, front or side plate, their ability to use weapons. Size and fit was found to be extremely important and a critical factor in improving ergonomic performance. All of these trials were on military armours which is designed to protect against different threat levels than police or security forces armours.

2.12 Test Methods

Standard methods to assess the ergonomics of different armours are not included in many Body Armour Test Standards and of those listed below only the CEN prEN ISO 14876 Standard (2001) - Ballistic Knife & Spike, includes a section on ergonomics. This European standard was rejected by CEN in 2002 although the CEN/TC 162/WG 5/PG 5 Committee revisited the Standard in 2008.

2.12.1 International Body Armour Test Standards

UK HOSDB (2007) - Ballistic, Knife & Spike[52]
USA NIJ 0.101.06 (2008)- Ballistic[70]
USA NIJ 0.115.00 (1999) – Stab [71]
NATO STANAG 2920- Ballistic [72]
German VPAM & PTI (2008) – Ballistic[73]
Russian GOST-R 50744-95 – Ballistic [74]
CEN prEN ISO 14876 Standard (2001) - Ballistic Knife & Spike[75]
German standard DIN 52290 (Technische Richtlinie Schutzwesten [76]

There are many general and product specific standards relating to Ergonomics in the workplace. A good starting standard is BS EN ISO 15537:2004[77] which provides an excellent general overview for the selection and use of subjects in trials for industrial products and designs. It defines the critical anthropometric measurements of typical body types for both World-wide and European human body sizes, recommends the number of test subjects according to relevant percentile of the user population and defines a procedure for designing a test programme. For preliminary tests (screening tests) it recommends using at least three subjects, for detailed tests seven subjects are recommended and these should be selected from the smallest to the largest persons expected in the user group.

A more detailed approach and a good source of information specifically relating to personal protective equipment (PPE) is included in BS EN 13921:2007[78]. This standard advises that any adverse effects on the user of wearing PPE should be minimised. It recommends ergonomic assessments should be carried out by subjects wearing PPE and that the assessments should be as objective as possible. However, it accepts that some aspects of the assessment may have to be subjective as some trials will inevitably be effected by the perception of the individual subject. It provides guidance in section 5.1 table 1[78] for potential tests to verify ergonomic performance and advises that the final assessment of PPE should be by appropriate wearer trials. These trials should cover the ergonomic impact of PPE on wearability and acceptability. In Annex A it provides recommendations and details of assessing PPE by wearer trials using panels of subjects and notes that with human subjects these assessments should conform to the “Ethical Principles for Medical Research Involving Human Subjects”[79]. It also provides a list of the essential test parameters that should be considered for a wearer trial. In determining the number of subjects to be used in a trial it follows the recommendations given above in BS EN ISO 15537:2004[77]

BS 7754:1994 Garment evaluation by Wearer trials (1999)[80] is a more general standard covering all clothing. The primary aim of this standard is to establish the effects of wash and wear to failure of a garment and therefore the durability of a specific garment. It requires approx 10-12 test subjects for a wearer trial.

NATO STANAG 2138 (Ed 4). Troop Trial Principles and Procedures – combat clothing and personal equipment.) (1996)[81] This military standard gives guidance on how to carry out a troop trial and recommends that wearer trials are carried out on all types of military clothing. The number of soldiers in a troop is not defined but is typically between 30 to 40 persons.

There are several specific Standards relating to the Ergonomics of body armour and the following UK and International standards were reviewed as they all include ergonomics trials in their assessment of body armour.

ISO/FDIS 14876-1 (2002) [59] Protective clothing - Body armour : recommends that five males and five females should be available. Three subjects should be chosen from this group of ten for the wearer trial. If after the test the results are borderline two further subjects should be chosen to trial the armours. It does not make any recommendations about the body sizes of the subjects chosen for the trials

EN ISO 14876-1 (2000) [82]Protective clothing - Body armour, essentially this is the same standard as above which was not adopted by Europe but was approved by ISO. As above it recommends that five males and five females should be available. Three subjects should be chosen from this group of ten for the wearer trial. If after the test the results are borderline two further subjects should be chosen to trial the armours. It does not make any recommendations about the body sizes of the subjects chosen for the trials

prEN ISO 14876-1-(ISO/FDIS 14876-1:2005) [83] Protective clothing - Body armour is a document that has been modified from the previous ISO/FDIS 14876-1 (2002)[59] It requires six test subjects for ergonomic wearer trials and there is no requirement for three of the subjects to be male and three to be female. As in the standards above it does not make any recommendations about the body sizes of the subjects chosen for the trials.

CEN/TC 162/WG 5/PG 5 N – working document (2010) [84] is also based on ISO/FDIS 14876-1 (2002)[59] and requires six test subjects for ergonomic wearer trials and in this document there is a requirement for three of the subjects to be male and three to be female. There is also no recommendation about body sizes of the subjects chosen for the trial.

All of the ergonomic standards relating to body armour wearer trials require at least six test subjects preferably three male and three female to perform their ergonomics tests. ISO/FDIS 14876-1(2002)[59] and *EN ISO 14876-1 (2000)[82] require that a further two male and two female subjects should be available and if the results from the test with three subjects are inconclusive these two extra subjects should trial the armour and their results be added to the previous three.

2.12.2 Sizing

In the above standards body armour is sized according to BS EN340:2003[85] with three dimensions measured in centimetres for males and four for females, Figure 2.8. Both male and female are measured at the circumference of the waist and chest. Then from waist to waist over the shoulder, the extra female measurement is the circumference of the body at the bust.

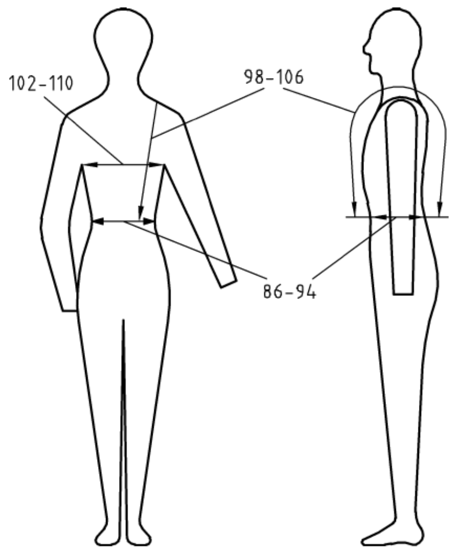

Figure 2.8 Circumference of body measurements (in centimetres) for a torso protector for men(after BS EN 340:2003[85], Annex D)

2.12.3 Classification

Both CEN and ISO classify each type of armour into seven classes with each class based on the different sizes of the zones of protection. They are labelled type A to G with the type referring to the area of the body that is protected, Table 2.8. For example type A has no protection over the shoulder and does not overlap at the sides. The types incrementally increase dependent upon the areas of the body protected up to type G which is protective over the shoulder, overlaps at the sides and has armour plates.

Table 2.8 Classification of Body Armour according to CEN and ISO body armour Standards

Body armour Classification	Area of protection	Position relative to pelvic bone (iliac crests)	Overt or Covert
A	No protection on shoulder Does not overlap at sides	<70mm	Covert only
B	No protection on shoulder Overlap or closed at sides	<20mm	Covert or overt
C	Protects shoulders Overlap or closed at sides	<20mm	Overt
D	Protects shoulders Overlap or closed at sides	>40mm	Overt
E	A pelvic protector attached to another type of armour	N/A	
F	An optional collar attached to another type of armour	N/A	
G	Armour plates to be worn in front of either armours A,B,C,D	N/A	

2.12.4 Coverage allowance factor

For CEN (EN ISO 14876-1) and ISO (ISO/FDIS 14876-1) a coverage allowance factor is based on these classifications and each type of body armour is allocated a number (coverage allowance factor) based on its classification. Table 2.9 compares the coverage allowance factors allocated by CEN and ISO.

Table 2.9 Comparison of coverage allowances

Type of body armour	CEN(EN ISO 14876-1)(2000) coverage allowance	ISO (ISO/FDIS 14876-1)(2002) coverage allowance
A	1	1.3
B	1.1	1.4
C	1.3	1.6
D	2.0	2.0
E	0.15 added to either A,B or C	0.15 added to either A,B or C
F	0	0
G	0	0

2.12.5 Performance level codes

CEN and ISO also allocate each type of armour a performance level code, Table 2.10. This code is based on the particular threat the armour is designed to protect against. The EN ISO 14876-1 (2000) standard, Table 2.10 has six ballistic performance levels coded from 0 to 5 with S denoting shotgun, 0 being bullet protection below level 1 low velocity handgun. Level 2 defined as protecting against high velocity handguns and up to level 5 which is protection against armour piercing ammunition. prEN ISO 14876-1-General requirements (ISO/FDIS 14876-1:2005) proposed performance levels of either 5 levels or as many as 15 levels.

Table 2.10 Performance Allowance *(ref:ISO/FDIS 14876-1 (2002) table 5)*

Projectile protection levels			Knife stab, and needle and spike stab protection levels			
Level	Allowances		Values of allowances for a vest with the same level of protection over its whole area. Add to the projectile protection level allowance. (types A, B, C and D)			
	For a vest providing the same level of protection over its whole area. (types A, B, C and D)	For armour plates (type G), increasing the level of protection of a vest. Add the highest appropriate allowance listed below to that of the vest alone. This will be for S, or for level 3, 4 or 5.	Knife stab		Needle and spike stab	
			Level	Allowance	Level	Allowance
1	0,4		1	0,25	1	0,25
2	0,7		2	0,5	2	0,5
3	1,5	0,5	3	0,75	3	0,75
4	2,0	0,7				
5	3,0	1,0				
S	2,0	0,5				
1 + S	2,0					
2 + S	2,0					
3 + S	2,0					
4 + S	2,5					
5 + S	3,5					

The current European working group CEN/TC 162/WG 5/PG 5 are suggesting four ballistic performance levels and these performance levels have not been finalised

2.13 Assessment after trials

ISO/FDIS 14876-1 (2002) is the only current approved body armour standard with ergonomics trials included in the standard. After completing the following set of actions, (none of which are specific police tasks):

- Fit and adjustability,
- Putting on and taking off,
- Office use and freedom of movement while seated,
- Standing with arm movements
- In front of body reach
- Lying down and getting up
- Running up and down stairs
- Irritation

The subjects are asked to score the armours as following:

- Score 0 - No problems
- Score 1 – Slight problem
- Score 2 – Problems of comfort or impediment
- Score 3 – More severe problems
- Score 4 – a severe problem

When a score of 4 is obtained a reason must be noted.
The ergonomic score is calculated by:
Adding the question scores of each panel member together separately
Dividing by the coverage allowance factor
Dividing their number by the total performance allowance factor determined from table 5 in the standard, (table 2.10 in this document.)

The average score of three subjects is then calculated
If the score is less than 0.8, the armour is satisfactory

If the score between 0.8 and 1, the test is repeated with two further panel members then the score is calculated from 5 panel members.

The analysis methods in the above standards are quite complex and Couldrick and Iremonger [63] were particularly critical of the scoring method which they felt was too subjective and rather faltering. The points in the scoring method are not well defined especially the mark for 'problems of comfort or discomfort' which as it does not relate to a specific area on the body is too vague to be useful. When armours of the same protection level are being compared the effect of this value cancels out. However, the area of coverage is a valid parameter that could be used to 'normalise' ergonomics tests on armours of the same protection level. The areas of coverage based on the area of the individual armours worn could be used resulting in a simple figure for area e.g. $0.4m^2$. The same method can be used to determine the area of the small, medium and large panels of each of the different armours under test. Should there be an armour with a high collar, more of the arms or armhole covered or a longer back, the area of that armour will be greater than the simple shape. The decision would need to be taken whether to include collars or arm protection as these items are not currently tested for their level of protection in any of the current standards. Once the area of an armour has been calculated the value obtained can be divided into its total score to normalise one armour against another.

2.13.1 Ranking Factors

An alternative to the area of coverage and possibly a simpler and more effective method may be to add 'weight' to certain tasks based on the level of importance of the task. For example tasks such as, how difficult is the armour to put into the carrier and how difficult is it to put on may not be considered as important as how difficult it is to drive, draw and fire a weapon or reach equipment on the officers' person. This last methodology has merit, in that the effect on the performance of the officer whilst performing his duties is taken into consideration. The most effective analysis would be to use both the area of coverage combined with weighting factors for essential tasks to analyse the data.

2.14 Summary

Based on the review above of the threat and vulnerability of the head and ergonomic factors there is still further work that could be done in these areas.

There is still much to investigate in measuring the forces behind helmets as behind armour effects have not yet been fully quantified for ballistic impact**.** Impacts at ballistic strain rates may be similar to those caused by tertiary blast. Current test standards have been developed for low velocity impact and the currently accepted standard values are 400g and 300g. However, the blast study by Makris and Bass[39] measured 799g for a head form fitted with a helmet and 754g without a helmet in a time period of less than 15ms. The fast rate of loading and the currently accepted standard values of 400g and 300g may mean they are not appropriate for the evaluation of the performance of combat helmets under blast or ballistic conditions. The available head injury criteria (HIC) for calculating injury thresholds for loading to the head have been developed for low velocity impacts. Work by Bass with cadaveric specimens has shown that HIC was not a good predictor for blast or ballistic head injury.

The CEN/TC 162/WG 5/PG 5[84] committee is still developing the CEN body armour standard and the author contributes to this work as a committee member. So the following chapters will address some of the issues such as establishing the optimum number of subjects for a valid ergonomics trial that could be used for Police trials and to determine a standard methodology for ergonomics trials.

In the UK, Military armour has been in service since 1979 and Police armour since 1999. As all armour tests are carried out on new armour there is little known about its reliability to perform after time so there is still work to be done in investigating the degradation in performance and reliability of soft and plate armours. The following chapters will address the issues raised in this review.

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Chapter 3. Historical

3.1 Development of Armour

The history of warfare has played a great part in the development of body armour, generally the development of every new weapon has lead to the development of armour to protect against it. As with any scientific study, before any work is undertaken it is prudent to examine and learn from what has been discovered before. In the case of body armour the timeline is very long. Since warfare began and well before it was documented man has been anxious to protect the most vulnerable parts of his body from personal attack by an enemy. In the past mainly due to the lack of medicines to control infections, even a small injury could quickly prove fatal. Initially early man required protection from blunt weapons such as stones, cudgels and clubs then as technology developed, sharp weapons such as axes, swords, knives and arrows progressing to the ballistic weapons of the modern day.

In the 21st century we may be taller than our ancestors but during the time period of recorded warfare the physiology of the human body has not changed significantly. The areas of the body requiring the most protection remain the same, primarily head protection for the brain with torso protection for the major organs such as heart, lungs, liver, kidneys and spleen[1]. Throughout history these areas were protected as without protection severe injuries to these parts of the body would inevitably be fatal. When protecting the body as they fought hand to hand on foot, it was important for the warriors of ancient civilizations to maintain their speed of mobility and manoeuvrability. So the ergonomic design of armour was a factor they understood could save their life and this important factor is still relevant for armour systems today. It is also interesting to observe the development of armour throughout the ages from different civilisations around the world. The methods in which early man solved the technological problems of protecting the body and maintaining manoeuvrability with the materials available to them still contribute to our knowledge base today and this will be discussed in more detail below. Horsfall[2] in his review described in detail many examples of patented armour systems copied directly from ancient systems. Some designs have been constructed from modern materials and supplied to the modern body armour market in the past twenty years[3].

3.2 Armour from Natural Materials

The hunting spear has known to have been in existence for over 400,000 years and the bow and arrow for about 30,000 year, Woosam-Savage[4]. Ancient systems were developed primarily to protect against spears, arrows and swords. Early man is most likely to have used natural materials such as treated thick animal hides to make protective armour. Following the introduction of metals for weapons breastplates of solid bronze, bronze scales [4] and iron chain mail [6] were developed to combat these weapons.

The Pitt Rivers museum in Oxford exhibits and maintains a collection of interesting armours made from natural materials collected mainly in Victorian times from isolated communities of the world, they give an insight into how the earliest types of armour may have been made.

Figure 3.1 Breastplate made from the back plates of the horny crocodile from Southern Egypt left, front surface, right back surface(body side). Founding collection formerly the Edward Meyrick collection 1884.31.1 (Courtesy of Pitt Rivers Museum)

It is recorded that as early as BC3100 that the ancient Egyptians [4] used animal hides for armour. The back plates from the horny crocodile back skin breastplate, Figure 3.1 illustrates how these may have looked. The age of the exhibit is unknown and only listed as being made before 1874 when the founding collection was donated. The arrangement of the scales of the crocodile skin above, resemble tiles or plates.

Figure 3.2 Close up of bony structure scales of horny crocodile
(Courtesy of Pitt Rivers Museum)

The ingenuity of the makers and the versatility of different types of skins used for armour are also illustrated in the armours exhibited at the Pitt Rivers. Among their collection are many examples of armours made from the thick hides of animals, one example is of rhinoceros hide armour, made by the Thado Kuki people from India. However, one of the most unusual is the war belt made of stingray skin
Figure 3.3, from Kiribati (Gilbert Islands). where the islanders have also used stingrays for weapons by fabricating daggers from the razor sharp barbs in the stingrays' tail.

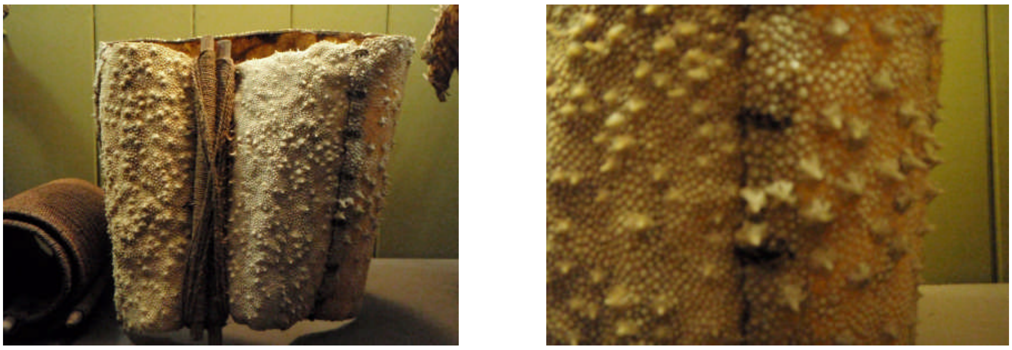

Figure 3.3. War belt of stingray skin and right: close up of skin surface (Gilbert Islands made before 1878) Courtesy of Pitt Rivers Museum

The Gilbert islanders were also very innovative in the other materials they used for protection. They fashioned full suits of armour from coconut fibres. Figure 3.4 shows a fibre helmet, body armour, undershirt and leggings with a spiny helmet of porcupine fish skin to fit over the coconut fibre helmet. The helmet and body armour are woven with a flat weave pattern and are different from the leggings and undershirt which are woven with a knotted pattern. It is difficult to determine whether these patterns are for extra protection, mobility or merely fashion.

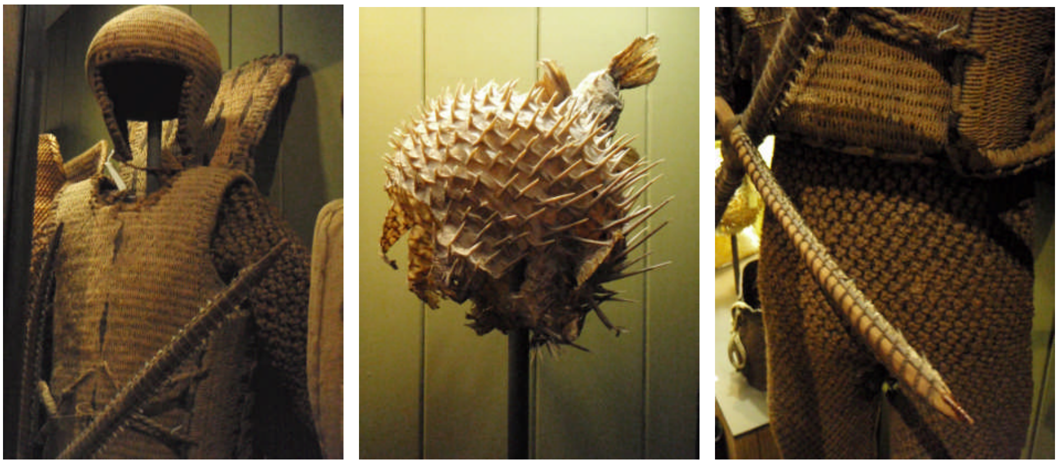

Figure 3.4 left: Suit of coconut fibre armour from the Gilbert Islands, centre: helmet of porcupine fish, left: detail of armour (Courtesy of Pitt Rivers Museum)

The high back plate on the armour is designed to protect the warrior from attacks by his own side, reputed to be from stones thrown at the enemy by women of his own tribe standing behind him [2]. The complete ensemble looks very cumbersome and uncomfortable to wear although there has been an attempt to achieve some flexibility with the different weaves used. It appears that protection is the major function of this armour system without consideration to comfort.

The amount of armour worn by ancient combatants depended on their role and infantrymen would have different protection from charioteers and spearmen [6,7,8]. However, the head was usually the first part of the body to be protected by a helmet with a shield being carried to protect the body [6]. Breast and back plates were developed for protecting the torso with shin protection called greaves for the front of the legs.

Similarly our modern day armour protects the most vulnerable areas of the body, the torso, head and sometimes the fronts of the arms and legs. The McBass body armour [5] for Australian forces is an example of a modern day fabric system offering leg and arm protection, Figure 3.5. The similarity in design of modern day armours to those of the past is noticeable.

Figure 3.5 McBas Australian Body Armour showing shoulder, neck, arm and leg protection ***(courtesy Aegis Engineering Ltd)***

3.3 Armour from Ancient Civilisations

Ancient civilisations have left us many records of their exploits in warfare either carved in stone or depicted on their art and these artefacts have shown us how they protected the combatants in their campaigns. The Louvre Museum in Paris holds the Sumerian 'Vulture Stele'[6] dating from about 2450BC, one of the oldest known fragments of stone relief depicting armoured warriors, Figure 3.6. This fragment from the Middle East records the victory of the city state of Lagash over its neighbouring city state of Umma in Mesopotamia (modern day Iraq) and shows the victors wearing helmets, carrying shields whilst trampling the dead bodies of their enemies.

Chronologically this date is comparable to that estimated by archaeologists for the construction of Stonehenge in UK[7].

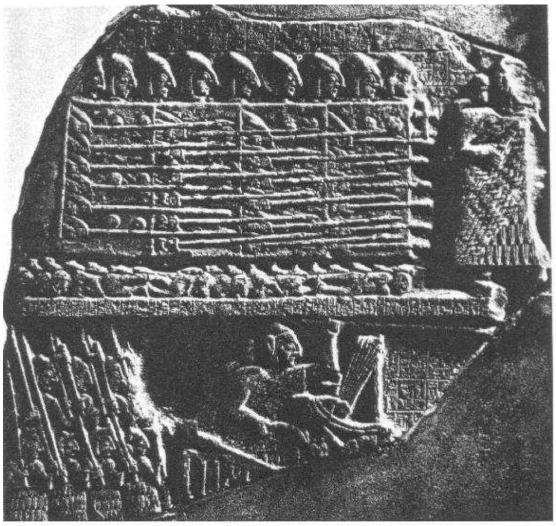

Figure 3.6. The 'Vulture Stele' 2450BC, from the Sumarian states of Lower Mesopotami (Image courtesy of Musèe National du Louvre, Paris.)

Fifteen hundred years later (1100-700BC) the Assyrians (modern day Northern Iraq) depicted their heavy infantry armed with a shield, a helmet and a leather tunic covered with metal plates.

Figure 3.7 Lightly armoured Assyrian cavalrymen (left) archers (right), (1100-700BC) Images courtesy of British Museum London.

This was in contrast to the cavalrymen and archers, Figure 3.7, whose lightly armoured torso and head protection allowed more mobility as they moved forward with the light infantry. The Greek Hoplites, Figure 3.8, were renowned mercenaries around 650BC and helped the Egyptians in their wars against Assyria[8] at this time. Their exploits were recorded by the earliest known historian of warfare, the Greek Herodotus [9]. The earliest Hoplites were armed with helmets of bronze, shields and wore greaves to protect their shins and breast and back plates, Figure 3.8. Archaeologists have attributed their name to a derivation of the word hoplon which can be used to mean a shield[6]. Their typical weapon was a long spear used in a thrusting action and in battle they would line up overlapping and interlocking their shields to provide protection to their bodies and an impenetrable barrier to the enemy. The long spear allowed them stab at their enemies from behind this barrier[10].

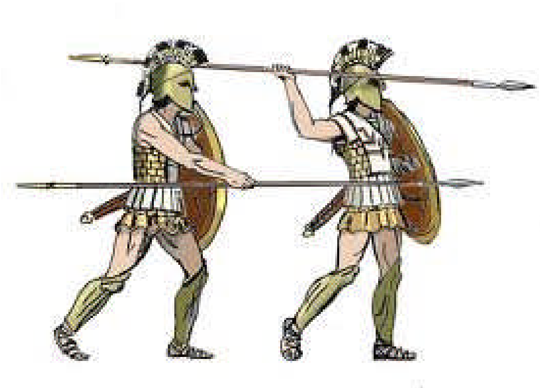

Figure 3.8 Hoplite warriors, wearing helmets, body armour and greaves, right: bronze Corinthian (Hoplite) helmet 5-8th Century BC (courtesy of Pitt Rivers Museum, Oxford)

Their heads were well protected from cuts and blows as the shape of the hoplite helmet protected the skull and most of the face. The greaves protected their legs but the body armour was not too heavy so their mobility and ability to fight was not compromised.

3.4 Roman Armour

In building their Empire the Roman state expended much time and effort in developing armour (Lorica) with state run factories producing armour[11]. They produced flexible chain mail armour (Lorica hamata)[4] from the 1st Century BC to the 5th Century AD, Figure 3.9 and scale armour (Lorica squamata)[4] which was small pieces of bronze or iron mounted onto a leather or fabric backing. It is interesting to compare the ancient systems illustrated in Figure 3.9 with their modern day equivalent knife resistant systems. The patterns are remarkably similar, only the materials used differ. With the advancement of technology stainless steel is now used for mail (left) and many of the current knife resistant systems worn throughout the world still incorporate chain mail in their design.

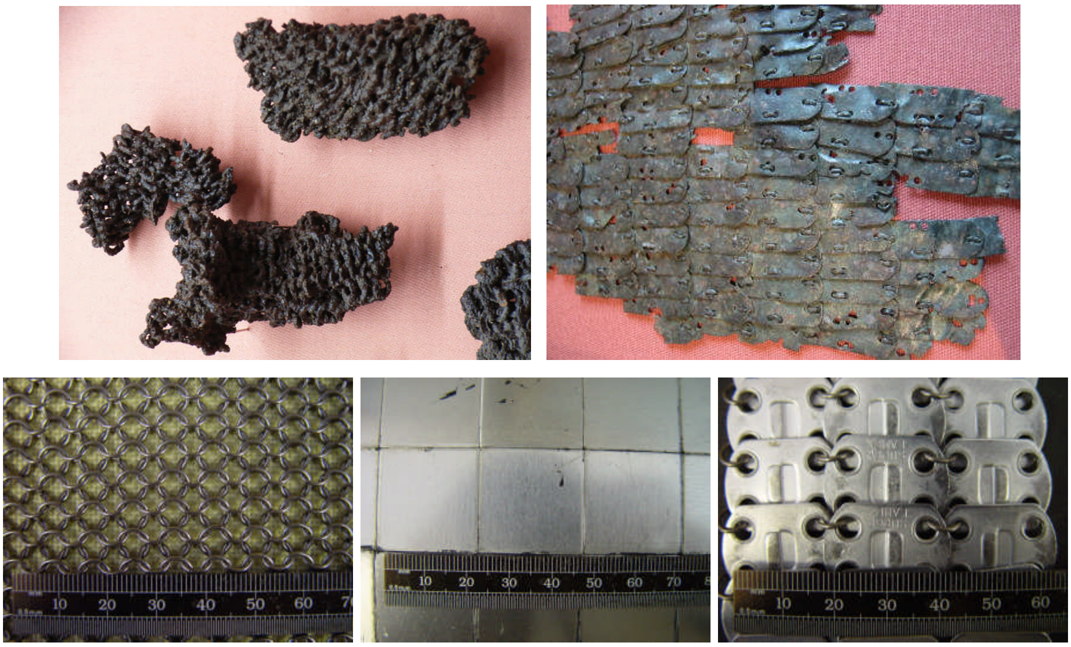

Figure 3.9 Examples of chain mail, Lorica hamata (right) and scale armour Lorica squamata compared with examples of their modern equivalent. Images courtesy of Carnuntinum Museum, Bad Deustch, Austria and modern armour collection, Cranfield University.

Small aluminium tiles are bonded onto an aramid backing (centre) rather than stitched onto fabric or a leather backing. The aluminium tiles in the right hand image are joined at each corner with metal rings, almost a direct copy of the 2500 year old squamata.

In 1964 on Hadrian's Wall at Corbridge, Northumberland a "hoard" of armour was uncovered. This find was largely responsible for the now accepted design and understanding of how plate armour (Lorica Segmentata) was constructed and used, Figure 3.10. The plates of this sophisticated system overlap and are well articulated over the arms and shoulders to allow the arm freedom of movement. The body sections overlap and can slide downwards to minimise restriction of the torso when bending. This armour offers good protection combined with flexibility. These properties are still valid today and with modern materials they are not always easy to achieve.

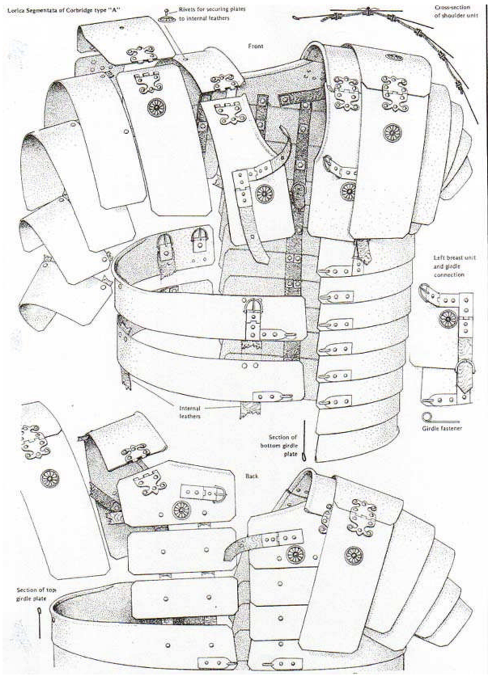

Figure 3.10 **Lorica Segmentata (Corbridge pattern) illustrated by Peter Connolly**

Roman helmets[11] protected the head and originally were very simple bowl shaped items, with no cheek pieces or crest holders. The Manneheim helmet is an example of this type from the early period of the Cesear Augustus 50-25 BC. Figure 3.11. In a later example the Weisnau helmet from 5BC-14AD there is added protection for the head with the addition of a neck guard and cheek flaps to protect the face. The neck guard is fixed and the chin pieces are hinged to allow a little movement.

Figure 3.11 Comparison of early Manneheim (left) with late Weisnau (right) period Roman Helmets showing development of face protection.
Images courtesy of Landesmuseum, Bonn, Germany and Carnuntinum Museum, Austria

3.5 Chinese Armour

The Chinese were also developing armour at the same period and a treasure trove was discovered in 1975 in the burial mound of Qin Shihuangdi, China's First Emperor[12] and ruler of the Qin Dynasty (221-210BC). Chinese armours of the Qin era were replicated in terracotta and they have added to the knowledge of arms and armour of that period. The body armours depicted by the terracotta warriors also show how sophisticated armour had become in the East. Their understanding of body armour protection and how it interacted with the body for the different requirements of the individual soldier can clearly be seen. The design for upper arm protection in particular bears a striking resemblance to that modern day armour in Figure 3.5. Figure 3.12a, shows an infantryman, his armour is made of small plates, either of leather or iron which are laced together with silk cords in intricate patterns to allow the plates to articulate in certain directions. This particular example shows the plates even accommodate his rather rounded stomach. The plates of some of the early Chinese armours were made of ox or cowhides with the top surface lacquered with many coats of natural resins to give a hard cut resistant surface [7]. What appear to be rivets in the armour[13] are upon closer examination silk knots, tying the armour plates together.

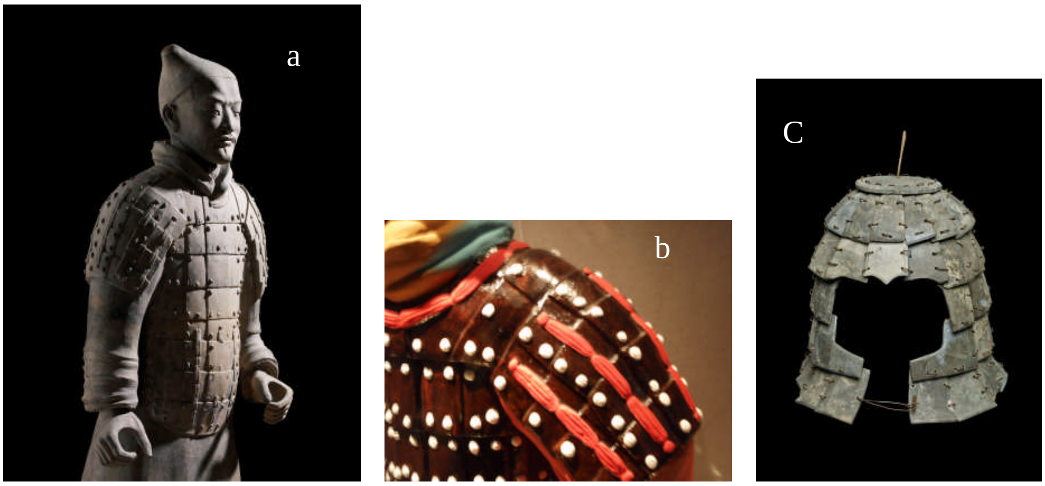

Figure 3.12. a) Terracotta warrior- armoured infantryman, b) detail of upper arm protection showing lacing and knots, c) Stone helmet.
Images Courtsey, British Museum, London. UK

The plates on the upper arm, Figure 3.12.b, are laced so that the bottom row can move up and over the upper rows and part of the chest/shoulder allowing the arm to be raised easily. There is one row of plates down the centre of the chest and the plates on each side of this row overlap outwards to the sides of the body, with the final rows of plates being shaped around the armhole and shoulder. The stomach protection is laced so that the articulation is towards the waist allowing the plates to move upwards when the soldier bends. Underneath the soldier wears a padded undershirt thought to have been of silk with wadding which would be a good absorber of any impact energy. The neck is closely protected by a scarf arrangement which also looks to be padded. Provision of armour depended on rank and the hierarchy of the army shows that higher ranking officers are depicted wearing a double layer tunic under a fish scale armour apron. Stone armour found in a burial pit away from the main burial site replicates tunics and helmets thought to be copied from suits of iron armour. The helmet construction, Figure 3.12c, shows that it is well articulated to give flexibility whilst protecting differing head shapes and should provide good protection to the head with the last layer of plates flaring out towards the shoulder which should protect the neck. The terracotta army do not have helmets or shields and are shown wearing felt caps or elaborate knotted hairstyles. Archaeologists hypothesise that as the terracotta armour was effectively ‘on parade’ in the presence of their emperor it was not in battle formation and therefore it was not required to wear battle helmets or shields. The examples of articulated plate helmets replicated in stone are considered as evidence that these helmets may have been worn on top of the felt caps as literary sources of the time record the wearing of helmets[7]. This is supported by further evidence in that the stone helmet also replicates an iron helmet found in tomb 44 at Yixian[14]China.

3.6 Medieval Armour

After the Romans, the major developments of armour were in the Medieval (1000-1600) period where knights continued to wear mail and also plate armours over padded leather jerkins[15]. Articulated plate armour was refined in this period until the whole of the body could be protected [4,15] Figure 3.13. Although plate armour covered the body completely the plates varied in thickness and were not excessively heavy, Edge[15] has measured the weight of a typical breastplate of the period at 2.7kg and its matching back plate at 2.3kg. This weight is comparable to the front and back of modern day armours and lighter than some [3]. Plates articulated in differing directions on the body were used so manoeuvrability during fighting was not compromised. To prove this re-enactors at The Royal Armouries in Leeds regularly stage demonstrations of combat whilst wearing plate armour.

Figure 3.13 Left: Replica of Norman mail armour (circa 1066), right: Henry VIII 16th Century plate armour. Source: www.medievalrepro.com and Royal Armouries, Leeds UK

3.7 Japanese Armour

Plate armours were also worn in the East during this period with the Japanese Samurai warriors (1333-1573)[4] armour being a good example of a light and very flexible armour system. Samurai usually fought as individuals in a very formal procedure similar to a duel[16]. Their armours were a complex arrangement of small tiles and mail joined together with intricate woven silk patterns and knots. Figure 3.14 shows an example of a full suit with details of the articulation of the elbow by joining the two sets of vertically aligned lamellar plates together with a net of chain mail at the elbow. The greaves on the front of the leg are constructed from plates laid together vertically overlapping from left and right to the centre of the leg. This would mean that there would be an allowance for side movement on the leg as the Samurai moved.

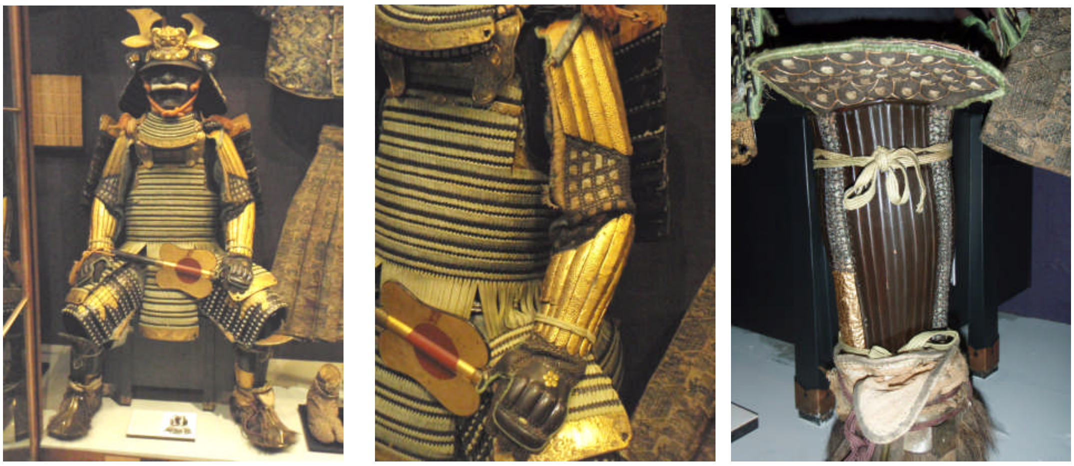

Figure 3.14 Samurai warrior armour showing complex arrangements of plates and mail to achieve flexibility and manoeuvrability
Courtesy Pitt Rivers Museum, Oxford (1941.4.58)

The plates of the breast plate and apron of this armour are stitched in such a way that they articulated in an upwards direction when the torso bends allowing the maximum amount of manoeuvrability when fighting.

With the introduction of firearms into warfare during the 17th century plate armour became obsolete as musket balls could penetrate the plate armour. Steel armour was made thicker but the increase in weight meant that it was un-wearable[17]. Helmets were still seen as useful[4] presumably due to the combination of protecting against blunt trauma to the head and the head being a small target for the accuracy of the ballistic weapons of the time.

3.8 17-21st Century Armours

Plate armour did not reappear again until the 20th century in the First World War (WW1). Soldiers in their trenches were protected from the major threat of wounding from rifle fire but not from wounding from fragments from exploding shells[17]. There were many experimental plate armours but none as extreme as the US Brewster armour[18] which protected the head and the torso.

Figure 3.15 Brewster body shield and Dayfield Body armour (1917) with silk neck defender [18]

It was designed primarily for sentries and to prevent the armour being penetrated by rifle fire the plate armour had to be thick and heavy. The body armour was made from chrome/nickel/steel armour and weighed 18.18kg (40 US pounds). The weight of the helmet is not recorded but its inventor Dr Brewster was the guinea pig for the trial and the photograph Figure 3.15, shows that he survived being hit with Lewis machine gun bullets at 830 metres per second. A more wearable solution was the Dayfield[18] body armour which was still made of steel plates but had a silk collar for neck protection. The Germans also made heavy body protectors and their design shown below is remarkably similar to the shape of the frontal assembly of a modern day explosive ordinance suit.

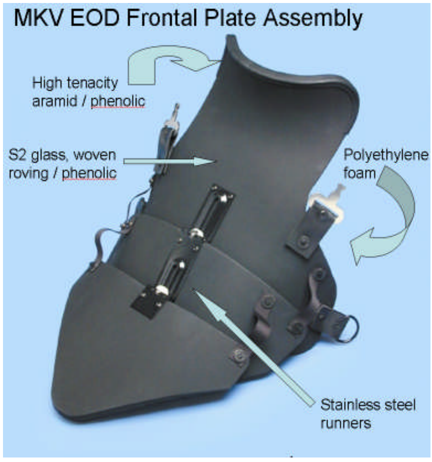

Figure 3.16 Steel German Infantry body protector 1918,(internet source) right modern EOD frontal assembly (courtesy NP Aerospace Ltd)

Because of trench warfare and the vulnerability of the head, helmets were introduced early into the First World War initially by the French[4] named the 'Adrian' Casque[19] and then by the British 'Brodie' and German 'Stalhelm'.

Figure 3.17 WW1 helmets (left) French 'Adrian' casque [19], (centre) British 'Brodie' [militaryhistoryworkshop.com internet sourced] and (right) German 'Stalhelm' [courtesy Pitt Rivers Museum Oxford)

These helmets were simple bowl shapes and comparable to the 2500 year old Weisnau roman helmet illustrated in Figure 3.11 above.

Little military body armour development occurred in the twenty years between the two World Wars [4,17]and WW1 helmets were still standard issue at the outbreak of war in 1939. Soldiers were not issued with body armour in WW2 but because of the number of casualties from heavy anti-aircraft fire, in 1943 American B17 air crews were issued with body armour consisting of overlapping manganese steel plates sewn into a canvas vest [4]. This armour weighed about 7.5Kg which when combined with all of the other equipment was considered quite an ergonomic burden.

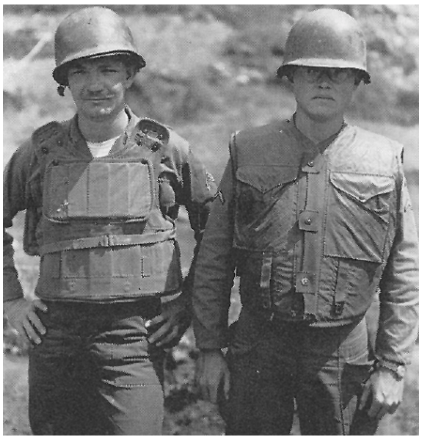

Figure 3.18 US Body Armour worn in Korean war T-52-1 body armour right, M12 left (after Tobin [17])

The Korean War saw the introduction of modern body armour for troops with the development of the US Marine Corps M1951 body armour made from plates of a new material Doron [17] which is a glass fibre reinforced composite material. Another all nylon vest the T-52-1, was also issued.

Dupont® synthesized the yarn Kevlar® in 1965 and it was commercialised in 1972 [20]. Kevlar® has a high tensile strength and it enabled the development of flexible fabric only body armours used to stop fragments. Body armour for UK forces was initially made from nylon was introduced in 1969 for the troops in Northern Ireland [21] but it was not general issue and was not worn by the troops in the Falklands campaign in 1982. There were a few (22) ceramic armours issued to helicopter crews in the Falklands campaign[21].

Military body armour and helmets still continue to protect mainly against fragments and the soft armour has some ballistic resistance but special plates need to be worn in front of the soft armour to protect against higher threats such as rifle fire. These plates can be very heavy and in some cases adding up to an extra 15kg of load to the soldier. There has been much development in the field of protection due to the need for casualty reductions in the recent conflicts in Bosnia, Iraq and Afghanistan. Generally this has resulted in more protection for the soldier. However it has been at the expense of manoeuvrability and comfort.

Kevlar Body armour for UK police officers was first introduced between 1973 -1976 and Brown[22] reports that in 1977 only 625 sets were in the UK. As a consequence of the Broadwater Farm riots of 1985 where PC Blakelock was stabbed to death [23] and another police officer was shot, body armour for UK Police was introduced more widely [2] firstly for firearms teams then for general use. Police body armour has been designed against a ballistic (handguns) and knife threat [3] and as in the military systems above, it protects against higher ballistic threats such as rifles when a plate is added to the soft armour.

Figure 3.19 An example of the problems caused from a poorly fitting armour

The Police encounter the same ergonomics problems as the military when wearing armour for long periods and military and police body armour systems can be heavy and cumbersome. They also do not always interact well with other items of equipment. The restrictions this imposes can affect the performance of the officer or soldier in completing their duties. Figure 3.19 shows an extreme example of this where the soldier is wearing armour that is too large in the confined space of a vehicle. The collar is interfering with the position of the helmet [24] and the ceramic plate in the armour is riding up the body towards the face.

There is still much that needs to be done to make ergonomically efficient armours that enable the wearers to complete their duties with the minimum of effort. The following chapters will utilise some of the historical developments described above on improving some of these issues.

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Chapter 4.

Assessment of blunt trauma under ballistic helmets

4.1 Introduction

Modern ballistic helmets are known to provide good penetration resistance against a variety of ballistic threats, and test methods to assess this are widely accepted [1,2]. These methods often include a test of the shock absorption, assessed by measuring the head acceleration which is then compared with suitable head injury criteria (HIC). Bass[3] has shown that the HIC is not necessarily an acceptable limit for skull fractures or brain injuries occurring from ballistic impacts. Anctil[4,5] has investigated the effect of deformation of helmets and resulting blunt impact to the head. Such impacts carry a significant risk of skull damage in addition to imparting high accelerations to the brain.

The purpose of this study was to measure impact forces with different sensors in an attempt to determine whether a relationship from the back face forces resulting from non penetrating impact and the forces required for injuries to the skull or brain can be found. The aim of the work was to evaluate these impact forces to develop a robust method of force measurement for helmet testing. Bullet impacts transfer kinetic energy onto a small area and whilst a helmet may prevent penetration of the skull and brain from the ballistic impact, back face deformation (BFD) of the helmet could result in high contact loads to the skull causing shock waves and consequently serious head injuries. The relationships between behind helmet impact forces, energy and brain injury have not yet been defined.

4.2 Preliminary trials

Forensic analysis by Wilber[6] and reported by Byers [7] established an empirical relationship between the amount of force necessary to cause a skull fracture from the deformation found on the frontal bone. From the examination of the weapons used in attacks and the depressions left in the skulls of cadavers of victims of fatal attacks, Wilber [6] related the size and shape of the permanent damage left by compressive fractures after fatal attack by blunt weapons such as hammers, to the radius of curvature of the impacting weapon, Figure 4.1. Wilber then replicated the attacks in the laboratory with the weapon used to inflict the injury and estimated the compressive force applied from the mass of the weapon and the acceleration (Force = mass x acceleration *(F= ma).*

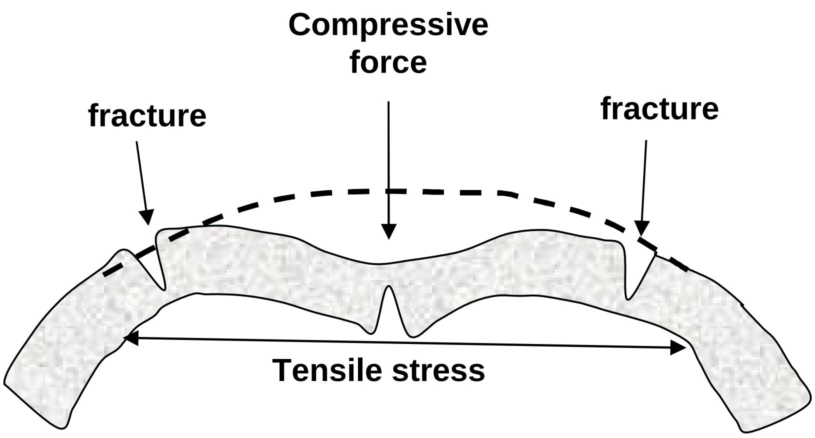


Figure 4.1 Skull fractures induced by impact force (after Byers[7])

4.3 Radius of Curvature

A program of ballistic trials was carried out to investigate if the radius of curvature caused by blunt weapons described by Wilber[6] could also be extrapolated to ballistic impact on helmets. Preliminary ballistic trials with 9mm ammunition fired from a proof barrel at 5 metres were carried out. To ensure that the ballistic impacts caused measurable BFD in these initial trials only the shells of aramid helmets without impact mitigating materials such as trauma padding or specialist liners and chinstraps were used. The constructions of the helmets used in these trials were commercial-in-confidence and therefore it is not possible to publish a detailed description. Permission was also not granted for describing the exact ammunition used. The velocity range was 283 - 459 ms^{-1} all bullets were stopped and significant measurable back face deformations were seen.

Following the above trial, plastilina® pre-conditioned and calibrated as in a ballistic body armour test [8] was chosen as a suitable witness material to back the helmet shells and measure the radius of curvature of the indents behind the helmets. Trials at velocities that had produced measurable back face deformations with 9mm, 30cal and 50cal fragments[2] were carried out on the helmet shells Figure 4.13. The depths of the indentations in the Plastilina® block were measured and the radius of curvature estimated. These tests were repeated with a set of helmets with mitigating padding and chinstraps. Figure 4.2 shows the test results plotted and superimposed on the forensic data graph.

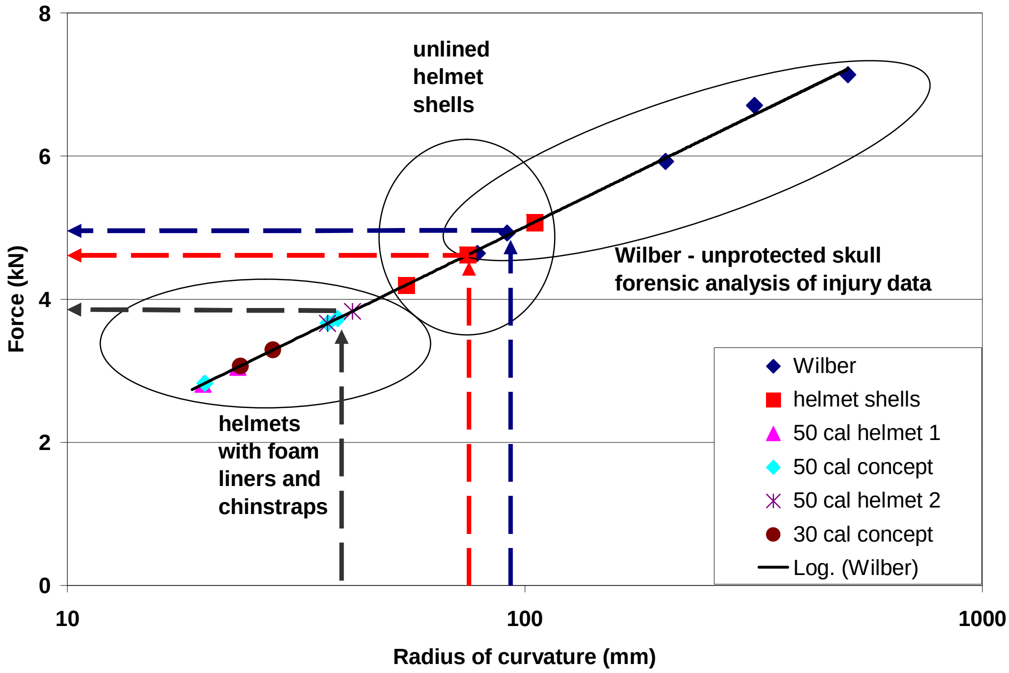
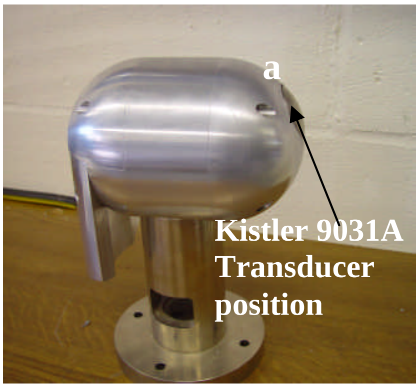


Figure 4.2 Comparison of estimated Force (kN) for skull fracture vs radius of curvature data from blunt weapons on unprotected skulls (Wilber[6]), used to derive potential skull fracture loads from the radius of curvature of ballistic impacts on helmets.

When plotted against the skull fracture loads reported by Wilber[6] the radii of curvatures from the ballistic impacts corresponded to estimated force values of 4 to 5kN, Figure 4.2. These force values and an average head weight (mass) of 5kg were used to derive acceleration ($F = ma$) which was found to be 100g. This result implies that the skull could be fractured by behind armour blunt trauma with accelerations of approximately 100g supporting Slobodik[9]whose investigation into US Army helicopter crashes concluded that the 400g limit of acceleration for survivability should be reduced to 150g.

4.4 Head form and calibration of Zephyr® sensors

To quantify and measure the impact forces a simple aluminium head form shape attached to a Hybrid III neck was fitted with a 9031A Kistler® force transducer with 60 kN measuring range and Zephyr® film sensors, Figure 4.4. These pressure sensors are readily available and inexpensive. It was hoped that the Zephyr® sensors would be able to pick up an average force over a fixed area throughout the impact event.



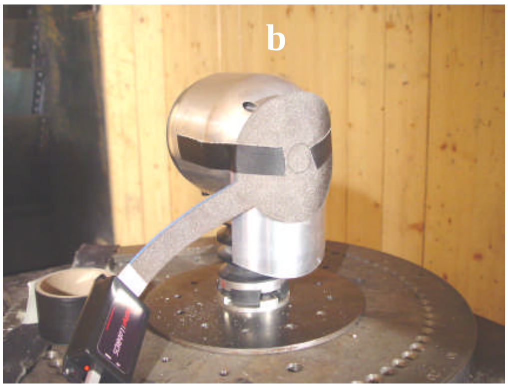


Figure 4.3 (a) Aluminium head form (on stand) showing position of Kistler® transducer b) Sensor attached to Aluminium head form and Hybrid III neck

The film sensors were flexible and easy to attach to the head with tape. The 25mm sensor pad, Figure 4.4 is positioned in the centre of a flexible polymer film sandwiched between two layers of foam. The exact composition of the measuring component was not disclosed by the manufacturer and no calibration data was supplied. The sensor samples at 250 kHz in 30ms and the output is an average of the applied forces across the sensor. In an attempt to validate the force output from these sensors a calibration method was developed and their outputs were compared with the force output from a calibrated [7,10] 9031A Kistler® compression load cell fitted into an Imatek IFW10 accelerated drop weight machine.

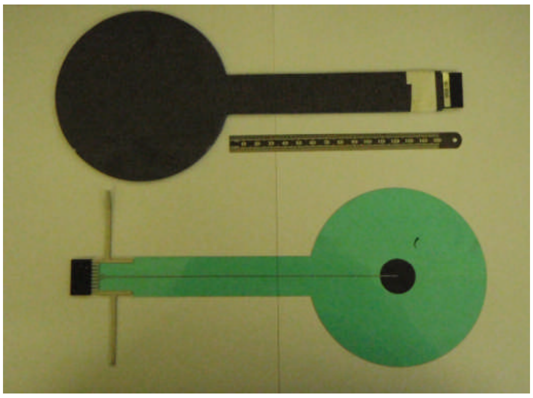


Figure 4.4 Zephyr® film sensor, inner measuring component (25mm diameter black dot) bottom and protective foam cover, top, 150mm rule included for scaling .

To compare and understand the effect of averaging of the applied force over an area three striker shapes Figure 4.5 were used to investigate the application of load over different surface areas. In the initial tests an aluminium base plate simulated the effect of the aluminium head form which would be used in the ballistic tests Figure 4.6.

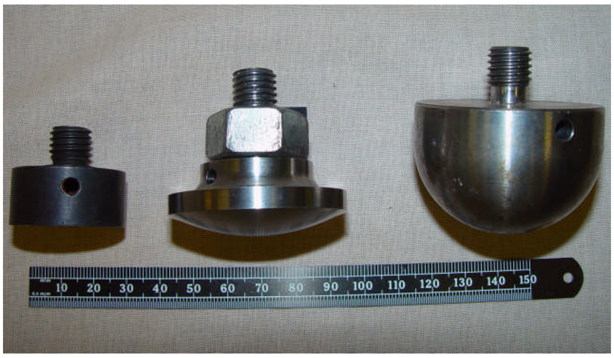


Figure 4.5 Striking tools used for the calibration of the sensors: left, 15mm diameter flat, centre, 50 mm hemispherical, right 25mm hemispherical

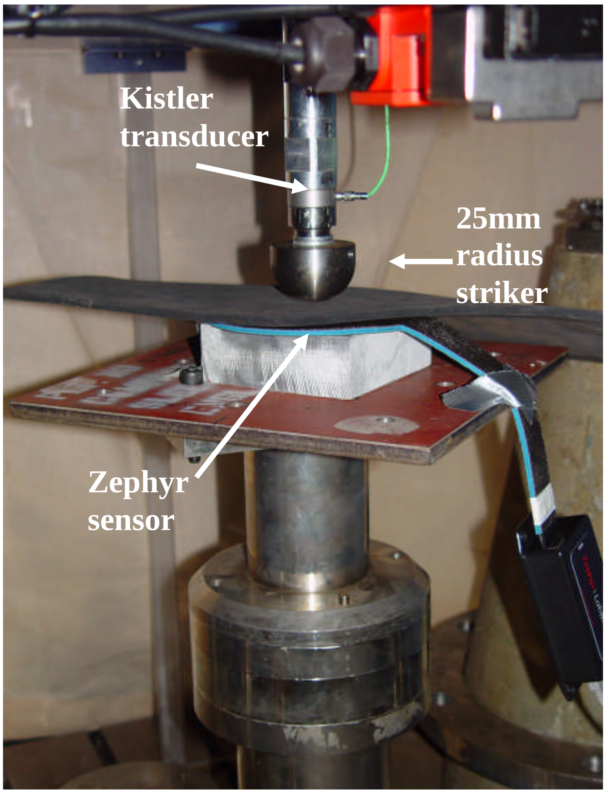


Figure 4.6 Striker assemblies and Drop tower calibration set up showing the 25 mm radius striker fitted.

Force, time, velocity and displacement during an impact event are measured by the Imatek IFW10 and as the mass of the falling weight is known the energy to fail can be determined. No electronic smoothing or signal processing filters were applied to the data as these can reduce the peak force values. The impact velocity for all drop tower tests was $1ms^{-1}$ with a mass of 8.64kg and Figure 4.7 shows a comparison of a typical force/time plot of the applied load from the 25mm striker from the Kistler load cell compared with the transmitted load measured by the Zephyr sensors. The sensor output was fed into a second data channel in the drop tower amplification circuits so the two sets of data could be compared. Typically the sensors appear to be measuring between 50% and 70% of the applied load. However this figure is a random number as the output was not in kN. The purpose of the calibration tests were to determine if a relationship between the values from the Zephyr® and the kN output from the Imatek could be established. The results from the outputs from the Zephyr$^{(R)}$ sensor, were not reliably repeatable which may be attributed in part to some of the forces being dissipated by the protective foam layers at either side of the sensor and that the sensor averages the forces of each impact across its surface area.

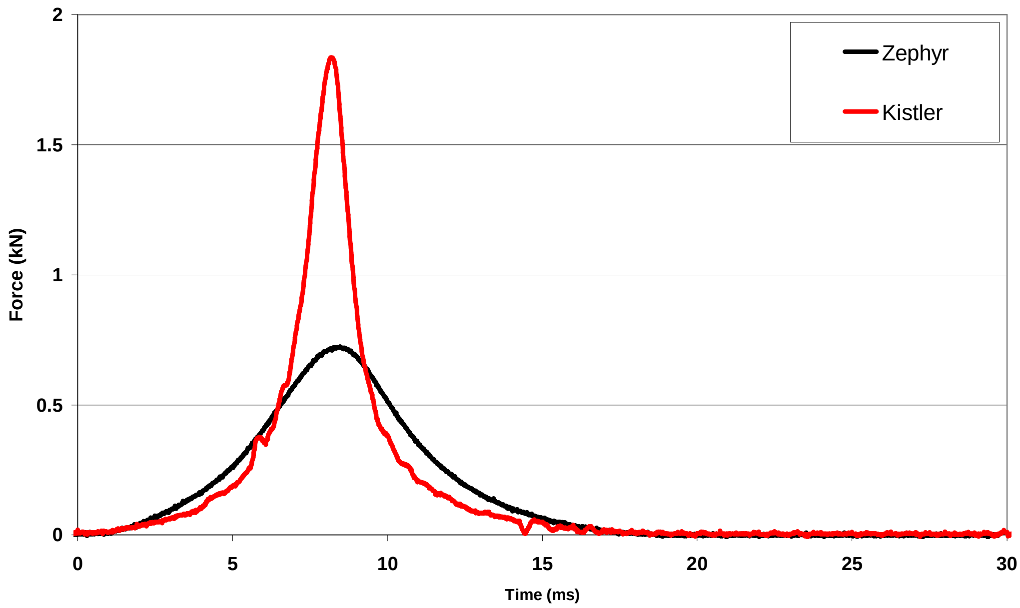


Figure 4.7 Comparison of impact Forces from 9031A Kistler® load cell and Zephyr® sensors with 25 mm hemi-spherical striker

Further series of tests with the different shapes of strikers were completed. The nominal peak force values for the 25mm striker were double those for the 50mm and 15mm strikers. As the measured force per unit area is averaged by the Zephyr® sensors this indicates that for this striker the impact forces were distributed over a smaller contact area, Figure 4.8. Although the outputs from the Zephyr(R) sensors were variable it was decided to include them in the ballistic trial to investigate their responses further. High peak forces over a short time would be expected from ballistic impact upon a helmet. Therefore the 25mm striker was selected for the calibration of the outputs from Zephyr sensors, transducer and accelerometers in the head form.

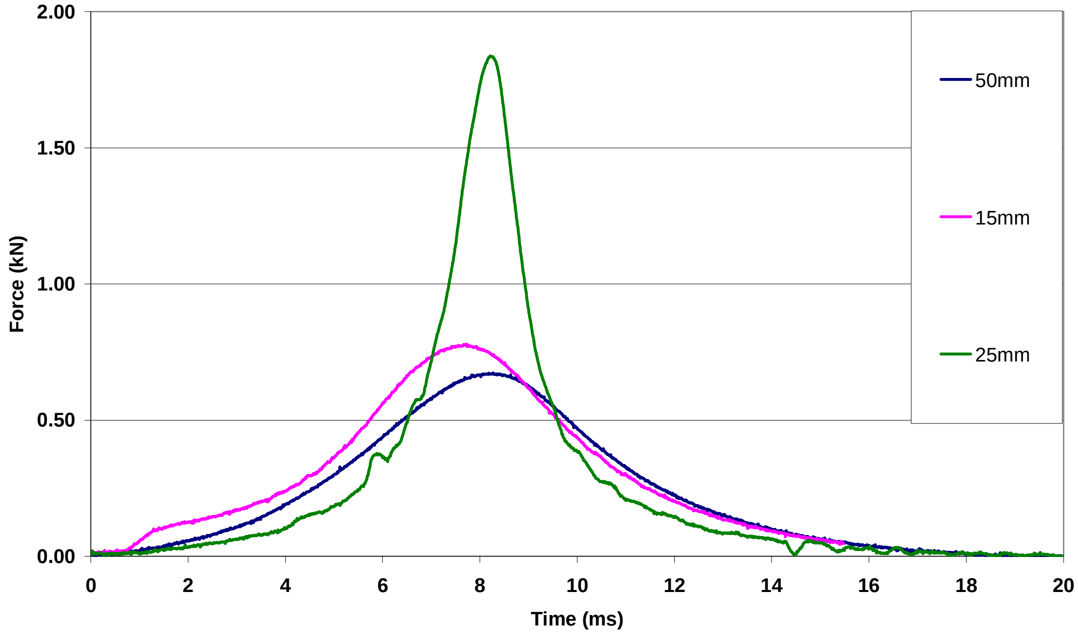


Figure 4.8 Comparison of Force vs Time drop tower traces of the three striker shapes

4.5 Calibration of the head form transducer

The 9031A Kistler ® transducer in the Imatek IM10 drop tower was also used to calibrate the force responses from the Kistler® 9031A transducer fitted into the aluminium head form mounted onto a hybrid III neck, Figure 4.12. The Hybrid III neck was fitted with three accelerometers to measure acceleration in the three different axes. For this work the direction of the axes were x axis (front to back) z axis (downwards) and y axis (side to side). The impact force responses from the transducer mounted in the head form show a good correlation with the force being applied, Figure 4.9.

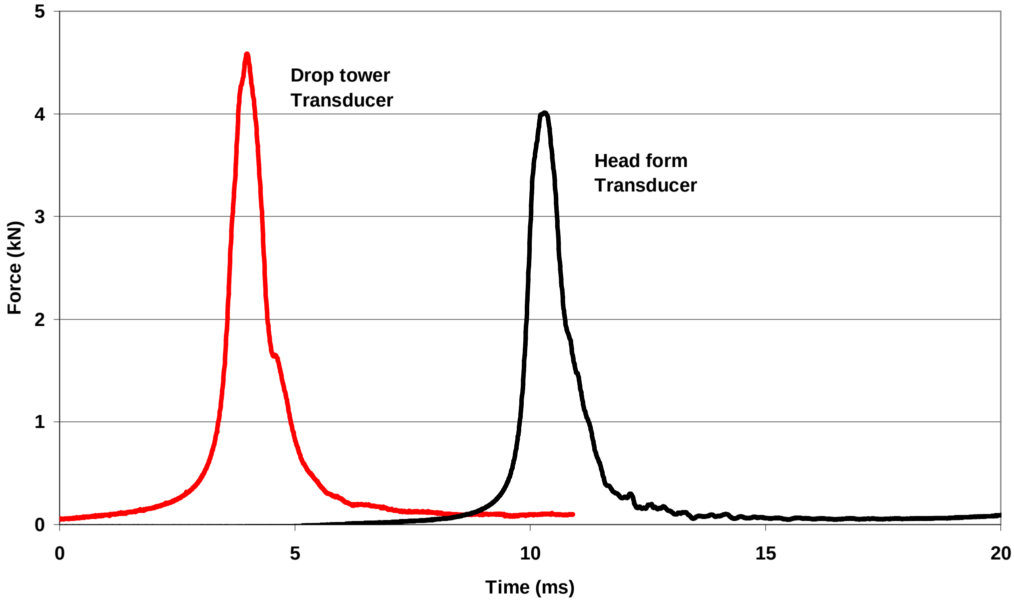


Figure 4.9 Comparison of force outputs from Kistler® transducer fitted in Imatek drop tower and head form.

Further drop tower tests to calibrate the force transducer outputs with the three accelerometer outputs were carried out with complete helmets (including their liners and liners and chinstraps fitted onto the head form, Figure 4.10. Using the least squares method the x, y and z axes accelerometer outputs were then summed to give a figure for total acceleration and multiplied by the mass of the head (4.82kg) to derive a force value to check the validity of the outputs from the system. The red curve in Figure 4.11 compares the peak force from the drop tower transducer (the applied force) of 7 to 8kN with the blue curve underneath from the peak force of 1.8kN measured by the head form transducer behind the helmet and shows the effectiveness of the helmet shell and padding in attenuating the impact forces.

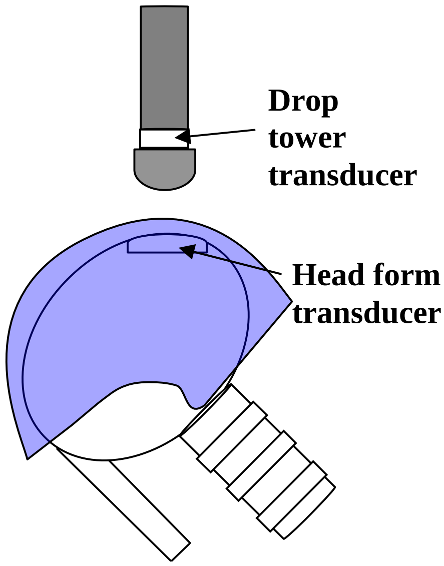


Figure 4.10 Diagram of head form positioned for drop tower impacts

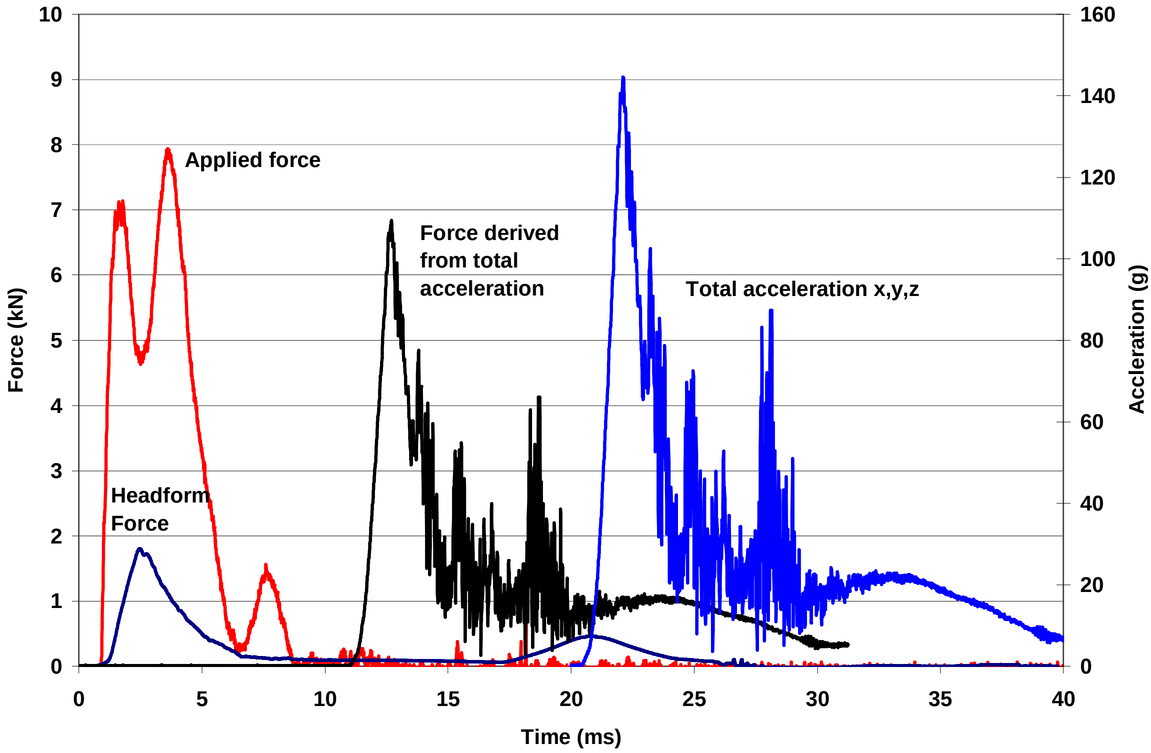


Figure 4.11 Comparison of Transducers and Accelerometer outputs

The applied force has a double peak due to the fact that as the compressive load is applied to the helmet the resistive force increases up 7.1 kN at 2.5ms. The impact causes the helmet to compress and move downwards on the headform. As the headform begins to accelerate it moves away from the striker and the compressive load relaxes momentarily so there is a corresponding drop in the force reading to 4.7 kN from the helmet surface. This is confirmed by the time period to the first peak which was 1.8ms being equivalent to the 1.85ms time to the single peak on the accelerometer signal. The loading continues as the striker and head accelerate together and the resistive forces increase again.

The sum of the outputs from the accelerometers is shown in light blue and the total acceleration of 140g is under the 400g limit of acceleration for survivability and correlates with Slobodik [5]. The force trace in black was derived from the total acceleration data and verifies the applied force data measured from the transducer. The time history of this test correlates with that seen in work on blunt impact and the 15-20ms duration of the force pulse is typical of time durations recommended for the calculation of head injury criteria (HIC).

4.6 Ballistic tests

Following calibration, both the head form transducer and film sensors were used to measure the forces and accelerations from the back face deformations of aramid helmet shells fitted with liners and chinstraps. These helmet shells were chosen as they had been previously tested with the 9mm ammunition, Figure 4.13 at a range of velocities from 280 – 450 ms^{-1}. These shells had exhibited significant back face deformations without perforation so it was expected that the sensors could be impacted without being destroyed. The helmet shell was positioned so that all shots that impacted the helmet imparted a load centrally on the sensor. The shots were positioned over the mitigation pads on the front right or front left temple or centre back with this padding in direct contact with the head form. No standoff distance from the head form was allowed and no skin or tissue simulant was placed over the transducer impact area. Six helmet shells were tested with at velocities of $360ms^{-1}$±10ms-1

Figure 4.12 Aluminium head form and Hybrid III neck showing transducer position, left. Aramid helmet shell with carriage system showing position of Zephyr sensor on right.

Figure 4.13 Ammunition used in the helmet trials 9mm round on left, 30cal and 50 cal, fragment simulating projectiles (FSP's) on the far right.

These test conditions combined with rigidity of the aluminium head form transducer mounting would measure the magnitude of the forces of a "worst case" impact scenario. Without extra foam protection some of the film sensors sustained irreversible damage during ballistic impact so a little useful data was collected from those tests. Although the response time of the sensors is fast enough for ballistic impact events the sensors will need further development to improve their robustness during the impact event.

The tests were repeated with the shot positioned so that they would load the transducer in the head form. The force traces from 9mm, 50cal and 30cal fragments[2] impacting the head form transducer positioned behind aramid helmets and the order of severity of the impacts are compared in Figure 4.14. Each shot was placed on the helmet so that the transducer would be correctly loaded along its centre axis. The smaller 30 cal fragment (2.84g at $473ms^{-1}$) imparted an impact energy of 318J and consequently had a lower peak force compared to the 540J from the heavier 50 cal fragment (13.39g at $284ms^{-1}$) and the 666J from 9mm (8g at $408ms^{-1}$) round.

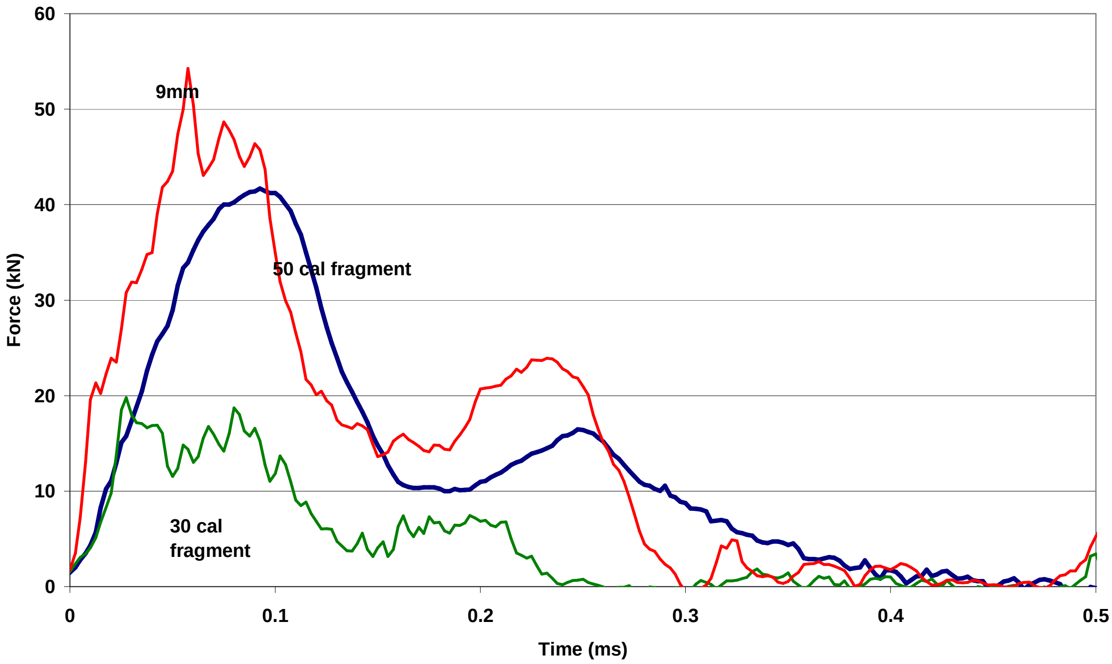


Figure 4.14 Comparison of force traces from head form transducer of 30 cal, 50 cal and 9mm shots.

The force readings recorded from the 9mm and 50 cal impacts are high and the peak acceleration of 940g calculated from the 50 cal impact is more than double the accepted 400g limit.

The time to reach peak force and acceleration and the duration of the pulse is short at typically 0.05ms or less. Analysis of high speed video of the event showed that upon impact the helmet deformed applying a force to the transducer, the helmet material then rebounded and resonated with the oscillations gradually being absorbed by the helmet, head form and neck movement. No acceleration of the neck was seen during the short duration of the ballistic impact event. Measurements from the high speed video showed the acceleration of the head and neck began at 0.69ms. The force trace derived from the total acceleration of the 50 cal shot is shown in Figure 4.15 and verifies the force data from the head form transducer.

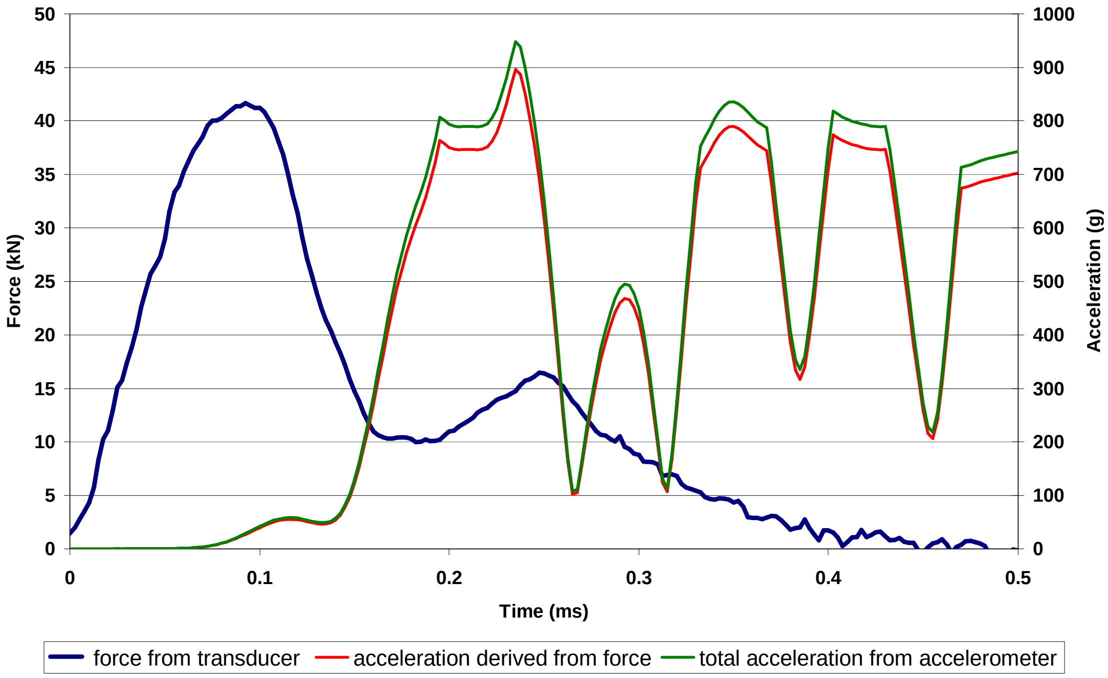


Figure 4.15 50 cal shot on head form with one helmet type, showing comparison of acceleration from accelerometer, force from transducer and derived acceleration from force transducer output.

Further 50 cal tests on three different ballistic helmet constructions, a helmet shell only and helmet numbers 1 and 2 (including their liners and chinstraps) are shown in Figure 4.16 and illustrate the potential of the head form test in differentiating between helmet constructions. The effect of increasing velocity on one helmet construction is shown in Figure 4.17. The results from 9 mm impacts stopped at 361ms^{-1} and 368ms^{-1} are compared with the high peak Force at 410ms^{-1} from a shot that was close to the V_{50} and almost penetrated the helmet and show the sensitivity of the force measurement. As no standoff distance was used in these tests the magnitude of the forces are high as the impact point directly in contact with the plate protecting the sensor.

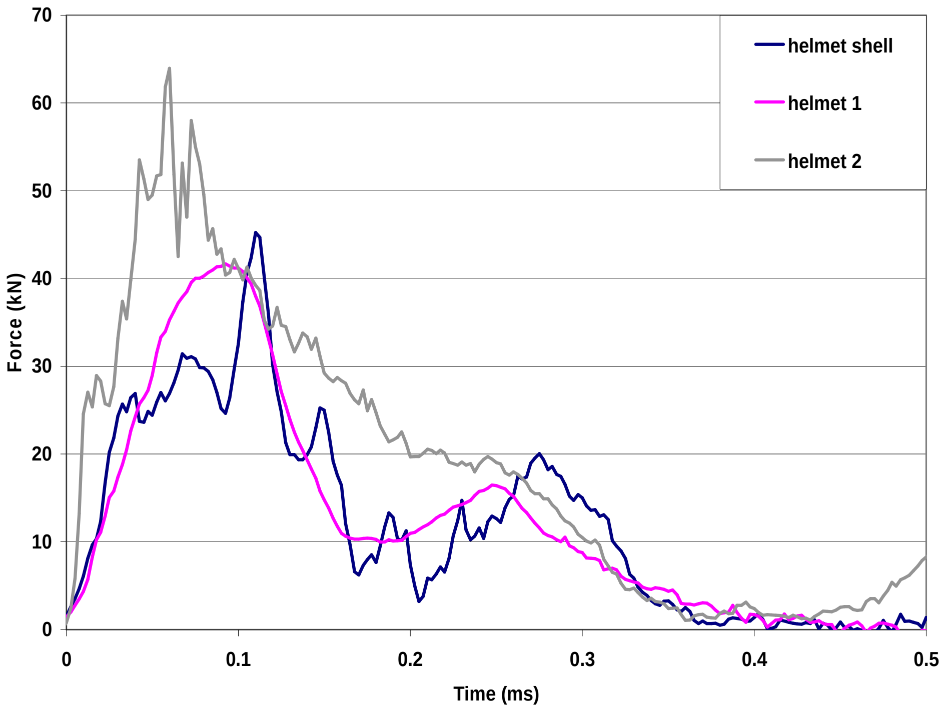


Figure 4.16 Comparison of force output data from the head form transducer of 50 cal shots on three helmet types

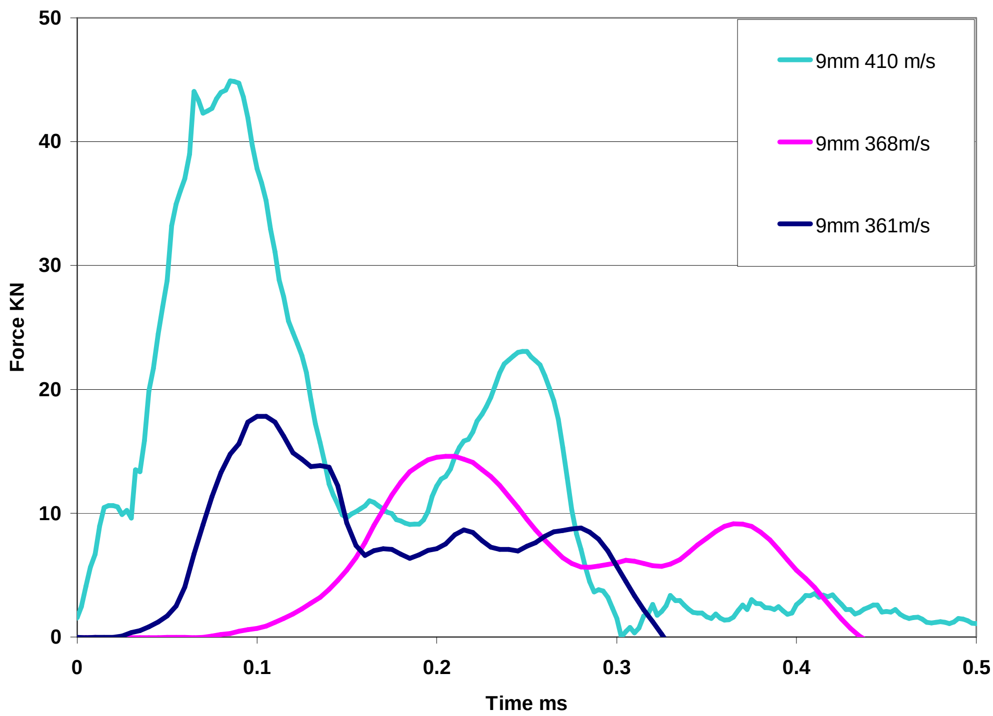


Figure 4.17 The effect of increasing velocity on one helmet construction

4.7 Summary

The results from this initial work show the head form was robust and could be suitable for simple ballistic tests as the peak force results were repeatable. The duration of the time of the ballistic impacts correlated with high speed video and similar work by other research groups [3,4,5] as did the timings to accelerate the neck. The 0.05ms duration of the peak force imparted to the head from ballistic impact is at a much higher rate than the 15.0ms duration rate accepted as suitable for the HIC calculations used for blunt impact. This concurs with Bass [3] who found that current HIC is not the best method to predict likely levels of head injury in ballistic events. However, the impact force results may be influenced by no standoff distance being used and the rigidity of the head form as it is not bio-fidelic. The Zephyr® sensors could not be calibrated reliably and were found to be too fragile for this type of impact test.

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Chapter 5 - National Police Improvement Agency Ergonomics trial

5.1 Introduction

In July 2008 at New Scotland Yard, London, the Metropolitan Police Service, the National Police Improvement Agency and the ACPO body armour sub-group announced an invitation to tender for the third generation of body armour to be issued to the Metropolitan Police Force. The requirement for the Body Armour was that it was certificated to the Home Office Standards & Development Branch (HOSDB) HG1A/KR1 Standard (2007)[1]. Four manufacturers of body armour were selected and their body armour certificated to the above standard at the UK HOSDB test laboratory which is part of the Impact and Armour Group, Cranfield Defence & Security at the Defence Academy College of Management and Technology (DCMT). To preserve confidentiality agreements the armours were coded by number from 1-6.

Once the correct level of protection had been achieved, the ergonomics of the body armour supplied was considered to be an important factor. Comfortable, wearable armour reduces the physical stress to an officer whilst carrying out his duties and a method to assess this was required. Previous wearer trials[2] involved 30 to 50 subjects issued with 2 to 3 types of body armour which were worn when the subject was performing their normal duties over a period of time. The number of subjects was rather *ad hoc* based on the number of units likely to be worn if 3000 units were ordered 1% would be tested e.g. 30. After a period of six months the wearer (subject) then completed a standard questionnaire after the completion of wearing each type of body armour. This method was very time consuming and expensive and had produced a sporadic response in the return of questionnaires from the officers involved in the trials. Often incomplete data sets were returned so that there was insufficient data for a conclusive evaluation.

The aim of the investigation would be to design a simple but intensive ergonomics trial that would be able to quickly compare the effects of the different styles and types of body armour carriers and their relative comfort/discomfort. Previous intensive trials with military subjects by Iremonger and Watson [3] had shown that very short simple trials could produce useful data on the ergonomics of body armour.

With the introduction of the UK Police Health and Safety Act (1997)[4] Chief Police Officers of the forty three UK Police Forces were required by law to provide a duty of care to all Police Officers serving in their Forces. This Act resulted in more body armour being introduced as personal protective equipment for all officers on general duties, rather than only to specialist firearms teams. Since the introduction of the Act it has become mandatory for all Police Officers to be issued with personal armour and it must be worn for duty.

The most important function of body armour is to offer the correct protection level with relation to the threat that may be faced by the wearer. Once this has been defined the next most important factor to be considered is how the armour interacts with the users' body and it should be as comfortable to wear as possible. It should not restrict or cause an unnecessary burden to the wearer in the performance of their duties. Wearer trials are expensive and time consuming to conduct and the trials results can be very subjective. Although wearer trials are a good method for comparing armour and detailed information on comfort and design issues, they do not always offer an objective and quantitative assessment of individual designs. Generally any item of clothing is easy to wear if it moves and flexes with body movements. Sports fabrics are an especially good example of extreme flexibility as they are designed not to restrict the sporting movements. The textile industry assesses fabric flexibility by a drape test [5] but this test is based on how a single layer of fabric drapes under its own weight. This method is not suitable for evaluating the flexibility of an armour panel that will consist of many layers. Most armour panels tend to remain flat and rigid and are not flexible enough to drape or fold under their own weight. It may be possible to bend or fold an armour panel in half but to be unable to fold the panel again or flex the panel in another direction. An ideal armour panel would exhibit sufficient flexibility so that as it is stretched in one direction it folds and contracts in other directions conforming to the change of body shape.

5.2 Ergonomic Wearer Trials - Test Methodology

Previous wearer trials for UK Police forces had involved 30-50 subjects wearing body armour when the subject was performing their normal duties over a period of time typically 3-6 months. This evaluation method of the previous wearer trials [2] had proved to be time consuming and expensive and the return of questionnaires from the officers involved in the trials were often incomplete. Anecdotal responses from the members of various Police forces to the Police Federation indicated that there was a general lack of confidence in the questions asked and in the results. They felt that wearing the armour day to day did not always test the correct parameters of the armours' performance. The prEN ISO 14876- 2002[6] test methodology was designed primarily to evaluate several movements whilst wearing body armour and part 4.11 Irritation (ISO 14876 Para 5.3.11.13) involved wearing body armour for up to six hours. However this standard is intended to apply to security guards duties and not all of the actions in this standard were considered to be relevant to Police duties.

The focus of designing this ergonomic trial would be to indentify body movements that were relevant to Police duties but would also assess a particular characteristic of a body armour system. Ideally the armour systems should not restrict the officer in carrying out his/her duties so normal tasks should be able to be performed. Armour flexibility and discomfort such chafing and pinching causing irritation were also perceived to be important factors. So to evaluate the ergonomics of the selected armour systems and to compare one armour system with another, a list of movements that could be directly linked to typical Police tasks was compiled. These movements included the assembly, adjustability and fit of the armour, some warm up exercises, an evaluation of movements in a vehicle and the general comfort and wearability of the armours. In addition the armours would be worn whilst performing some movements for Officer Safety tactics. These are a set of actions used in officer safety training [7] for self defence if necessary whilst dealing with riots. They are illustrated in figures 5.7, 5.8 and 5.9 below and comprise of drawing a baton and striking high and low onto a foam protector (simulating an attacker) and knee strikes to the front and side onto the protector. They also replicate searching and handcuffing a suspect and moving the suspect in and out of a car safely. Initially thirty volunteers would be used for trials on armours 1,2 and 3, with ten being used for armours 4,5 and 6 to investigate the minimum number of trial subjects that could be used for a valid data set.

5.2.1 Test protocol and Questionnaire

A test protocol and a questionnaire based on the movements identified above were written and submitted to the Metropolitan Police and Cranfield Health Research Ethics Committee for approval. The principle of the questionnaire being a one page form (figure 5.1) was important to reduce the amount of paperwork needed so the trial could be completed quickly. It was also important to get unambiguous data from trial so a simple form was designed with tick boxes and short explanations of the ranking system.

5.2.2 Ranking system

To ensure some clarity in the data a marking system of 1-4 points was chosen. With award points being 1 = Poor, 2 = Tolerable, 3= Good, 4 = Very good. The purpose of choosing 1-4 was to make a volunteer actually think about the points he/she had to award for each task and engage with the choice. If a marking system of 1-5 is chosen, with a middle value of 3 for neither good nor bad, there is a tendency for the majority of volunteers to choose the middle value as an easy choice or opinion. This of course does not help the analysis, as it does not highlight the differences between one type of armour and another. The objective was that the marking scheme would produce a high score for good armour systems. A spread sheet was compiled to process the data figure 5.2, marks were totalled for each task then these scores totalled and divided by the number of volunteers to obtain a simple ranking figure for each system.

Ergonomic Assessment of Body Armour **Date:**

Volunteer Number		**Male**		**Female**		**Amour Name/Type**	

Please tick one box for each question: 1 = poor, 2 = tolerable, 3 = good, 4 = very good

Assembly and Fitting
Remove armour panels from the carrier, read label, insert into carrier. How difficult are these actions?

	1	2	3	4		1	2	3	4
Is the labelling readable?					Is the armour easy to put on?				
Is the armour easy to put into carrier?					Is the armour easy to adjust to fit?				

Warm up	1	2	3	4		1	2	3	4
Running on the spot					Behind body reach				
Above shoulder stretch					Cross body reach				

	Yes	No		Neck	Armhole	Waist	Shoulder
Did the armour chafe?			If Yes where?				

Officer Safety Tactics
How difficult were the following safety tactics whilst wearing body armour?

	1	2	3	4		1	2	3	4
Knee strikes					Handcuff				
Draw baton closed mode					Prone search tackle bag				
Figure of eight strike					Stow tackle bag				
Extend baton and strikes					Move tackle bag across and out of car				

Vehicle evaluation
How difficult were the following actions in a vehicle whilst wearing body armour?

	1	2	3	4		1	2	3	4
Adjust seat, put on seat belt					Turn head to right, turn head to left				
Take an object out of glove box					General driving				
Maximum extent of reach (mm)									

General

	1	2	3	4
Was the weight of the armour good?				
Was the size and shape good?				
Good compatibility with rest of uniform?				
Was the weight distributed well over the body?				
How comfortable overall was this armour?				
How well does the armour fit?				

	Yes	No		Neck	Armhole	Waist	shoulder
Did the armour chafe?			If yes where?				
or pinch?							

Other comments
Please add any additional comments in the box below

Figure 5.1 Questionnaire

Ergonomic Master Score Sheet	Ergonomics Ranking																													
Body armour name																														
Protection levels	HG1A/KR1																													
Activity movement or assessment	1	2	3	4	5	6	7	8	9	10	11	12	13	27	28	29	30	19	22	23	25	14 F	15 F	16 F	17 F	18 F	20 F	21 F	24 F	26 F	Total
Is labelling clear	3	4	3	4	4	3	3	3	4	3	4	4	3	3	4	4	4	4	4	3	3	3	4	4	4	3	4	4	4	4	108
Easy to put in carrier	3	4	3	4	4	3	3	3	4	4	4	4	3	2	4	4	4	4	4	4	3	4	4	4	3	2	3	3	3	3	104
Easy to put on	4	4	3	4	4	3	3	2	2	4	4	4	4	3	4	4	4	4	3	3	2	4	3	4	4	3	2	3	2	3	100
Adjustment to fit	4	4	4	4	4	3	1	2	1	4	4	4	4	3	3	4	4	3	3	4	2	4	3	4	4	3	3	4	2	3	99
Running on the spot	3	4	4	4	4	2	3	3	1	4	4	4	3	3	4	3	4	4	3	3	1	4	3	4	4	3	3	4	3	3	99
Above shoulder stretch	4	4	4	4	4	2	3	2	2	4	4	4	3	3	4	4	4	4	3	3	1	4	4	4	4	2	3	4	3	3	101
Behind body reach	3	4	4	4	4	2	4	3	1	4	4	4	4	2	4	4	4	4	3	3	2	4	3	4	4	2	3	4	3	2	100
Cross body reach	3	4	4	4	4	2	4	2	1	4	4	4	3	3	4	4	4	4	3	3	2	4	4	4	4	2	3	4	3	1	99
Chafing	4	4	4	4	4	3	3	3	3	4	4	4	4	4	4	3	4	3	4	3	4	4	4	4	4	3	2	3	3	3	107
Knee strikes	4	4	4	4	4	2	3	3	2	4	4	4	4	3	4	3	4	4	3	4	2	4	4	3	4	3	3	4	2	2	102
Draw baton closed	3	4	4	4	4	2	3	3	2	4	3	4	3	3	4	3	4	4	3	4	2	4	4	3	4	3	3	4	3	1	99
Figure of eight strike	3	4	3	4	4	2	4	3	2	4	3	4	3	3	4	4	4	4	3	3	2	4	4	3	4	3	3	4	2	2	99
Extend baton and strikes	4	4	4	4	4	2	4	3	2	4	3	4	3	3	4	4	4	4	3	3	2	4	4	3	4	3	3	4	2	2	101
Handcuff	4	4	4	4	4	2	3	3	2	4	3	4	4	2	4	3	4	4	3	4	2	4	4	4	4	3	2	4	3	2	101
Prone search tackle bag	3	4	4	4	4	2	3	3	2	4	3	4	4	2	4	3	4	4	3	4	2	4	4	4	4	3	3	4	3	3	102
Stow tackle bag	4	4	4	4	4	2	3	3	2	4	3	4	4	3	4	4	4	4	3	3	2	4	4	4	4	3	3	4	3	3	104
Move tackle bag	4	4	4	4	4	2	3	3	2	4	3	4	4	3	4	4	4	4	3	3	2	4	4	4	4	3	3	4	3	3	104
Adjust seat clip seatbelt	3	4	3	4	4	2	2	3	2	4	3	4	4	3	4	4	4	4	3	4	2	4	3	4	4	2	2	3	3	1	96
Retrieve object from glovebox	3	4	4	4	4	1	3	3	3	4	4	4	4	2	4	4	4	4	3	4	2	4	3	4	4	3	3	3	2	2	100
Head turns	3	4	4	4	4	2	2	3	2	4	4	4	3	3	4	3	4	4	3	4	2	4	3	4	4	3	3	4	3	3	101
General driving	3	4	4	4	4	2	3	3	3	4	3	4	4	3	4	4	4	4	3	3	2	4	3	4	4	3	2	4	3	2	101
Weight good	4	4	4	4	4	3	3	3	3	4	3	4	4	3	3	4	4	3	3	3	3	4	4	3	4	3	3	3	3	3	103
Size and shape good	4	4	4	4	4	3	3	3	1	4	4	4	4	2	3	4	4	3	3	3	3	3	2	4	4	2	2	3	1	2	94
Compatibilty	3	4	4	4	4	3	4	3	2	4	4	4	4	3	3	3	4	3	3	4	2	4	3	4	4	3	3	4	2	3	102
Weight well distributed	3	4	4	4	4	3	3	3	2	4	3	4	4	3	3	3	4	3	3	3	3	4	3	3	4	3	3	3	3	3	99
Comfortable	4	4	4	4	4	2	3	2	1	4	3	4	4	2	3	4	4	4	3	3	2	4	3	4	4	3	2	3	2	2	95
Good fit	4	4	4	4	4	2	2	1	1	3	4	4	4	2	3	4	4	4	3	3	2	3	3	4	4	2	4	3	1	2	92
Chafe and pinch	4	4	4	4	4	2	3	3	3	4	4	4	4	4	4	4	4	3	4	3	4	4	4	4	4	3	2	3	3	2	106
neck						0	1	1	1									1		1						1	1	1	1	1	10
armhole						0	0	0	0									0		0						0	0	1	0	0	1
waist						1	1	1	1									1		1						1	1	1	1	0	10
shoulder						1	1	1	1									1		1						1	0	0	1	1	9
Totals	98	112	107	112	112	64	84	77	58	110	100	112	103	78	105	103	112	105	88	94	63	109	98	106	111	77	78	101	73	68	2818

Ranking

xxxxxx

Figure 5.2 Spreadsheet illustrating scoring of armour system

5.3 Pilot trial

When approval was received from both authorities, a pilot trial at DA-CMT using current and old armour systems was carried out by volunteers from Physical Protection Group of the Metropolitan Police and Cranfield staff under the supervision of an experienced Officer Safety Tactics trainer. This was in order to establish the timings for the trials. Also the protocol, robustness of the questionnaire and the significance of the chosen movements were evaluated.

The priority at this stage was to determine differences in the armour designs and to assess that the tasks were relevant to Police duties. It was essential that the trials were understandable and easy to explain to both the manufacturers our Police volunteers. Some tasks were more rigorous than others and a more complex system of ranking the tasks may need to be considered. At this stage no weightings for lighter tasks or operational effectiveness were introduced. The straightforward approach of giving each task the same level of importance in the marking scheme would reduce the amount of time explaining the method to the volunteers and processing the data. The conclusion of this pilot trial was that it was possible to determine differences in the armour systems by the movements chosen and the simple analysis.

5.4 Intensive Ergonomics Wearer Trials

Invitations and information packs for thirty volunteers to participate in the wearer trials for amours 1, 2 and 3 and ten volunteers to participate in trials for armours 4,5 and 6 were sent to all Police Forces by the Metropolitan Police trials co-ordinator. Volunteers were asked to complete the documents and bring them to the wearer trial, complete anonymity was guaranteed so that the officers were able to express their true opinions of the systems under test.

5.4.1 Body Armour Systems and fitting

Four armour manufacturers were asked to supply body armour to fit all the volunteers. There were six armour types supplied, two manufacturers sent one example each and two manufacturers sent two examples each. Although the armour panels were of a different construction for each of these last two examples they were in the standard design carrier for each manufacturer so the outer appearance of these armours looked the same as illustrated in Figure 5.3. There were some differences in the carriers supplied by each manufacturer. The design for armours 1 and 4 incorporated a ribbed nylon fabric at the sides, under the arms and on the shoulders.

Armour 1& 4

Armour 2

Armour 3

Armour 5 & 6

Figure 5.3 The four armours worn by volunteers in the ergonomic trial

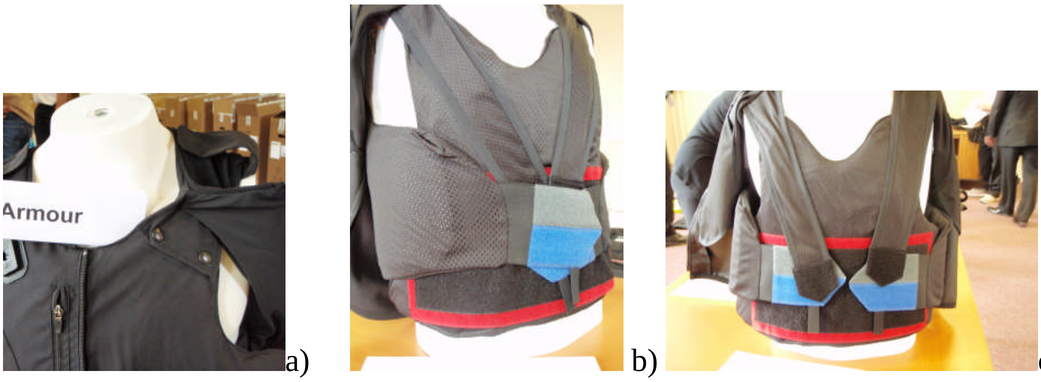
The manufacturer of armour 3 had chosen a similar ribbed nylon fabric for an inset around the armholes. The manufacturer of armours 5 and 6 had more ribbed nylon incorporated in their designs and a longer length of carrier that the officers' equipment belt could be worn over. Manufacturer 2 provided an all polycotton carrier.

The major differences in the carriers were the size of the armholes and neck. Manufacturer 2 had the most generous allowance at the armholes which were cut lower than the other two versions. The armholes of armour 3 fitted the around the arm snugly and this carrier also had a higher neck with a narrow integral collar and was slightly lower at the front, Figure 5.4a.

Two trained uniform fitters from The Police College Hendon were available at the trials, both had received specialist training in the fitting of armours 1 and 4 with a specialist harness and were familiar with fitting the other systems. These fitters were present at both DA-CMT and Hendon trials to ensure that each individual had their armour fitted personally. If a size could not be found for a volunteer and they could not be fitted with any one type of the three armours in the trial, these volunteers were discounted from the data set collected in the trial. All volunteers in the trial wore each of the three armour systems available so a direct comparison of one armour type with another on the day was possible.

Figure 5.4 a) Armour 3 integral collar b) Armour 1 (and 4) side panel design

All armours had a front zipper in the carrier to allow the armour to be taken off and put on as a jacket. However the front armour panel is in one piece to provide maximum protection to the front of the body and the methods to secure this panel when the zipper was opened differed between the manufacturers. Armour 2 had a small pocket on the inside cover of the left front so the front panel could be tucked into it at the bottom then secured with a press stud (popper) at the shoulder. The front panels of armours 1 and 4 were also secured under the overlap for the zipper, with two press studs (poppers). Armour 3 had two straps to secure the front panel then the waist belt could be fixed. However the fitters remarked that this design could be confusing as it could easily be fitted in two ways as illustrated in Figure 5.5.



a) b) c)

Figure 5.5 a) placement of press studs, Armour 1 (and 4), b) and c) Armour 3, strapping arrangement, for securing the front armour panel.

5.5 Ergonomic trial

5.5.1 Assembly, adjustability and fitting

After fitting, the officers were instructed to take out the armour panels from their carriers check the labels then insert the panels back into their carrier, adjust the straps and put the armour back on. This was to simulate being issued with their armour and re-assembling after washing the carrier. They were also instructed to wear their equipment belts to assess if the armour obstructed their reach of items such as handcuffs or batons.

5.5.2 Warm up

Before beginning the movements for officer safety tactics a series of aerobic warm up exercises were carried out under the supervision of an officer safety trainer. These exercises consisted of running on the spot, an above shoulder stretch, behind body reach, in front of body reach and a forward bend. The way in which the armour moved on the body during these exercises was very useful in indicating areas of potential chafing and irritation. Twisting the body during the bending movements was invaluable in determining the amount of flexibility any armour might have.

Figure 5.6 Warm up session

5.5.3 Officer Safety Tactics

The officers completed these tactics in pairs and they were carried out with much enthusiasm by all. The set of movements began with a knee strike onto a pad then the baton was drawn closed from the belt and a forward strike, multiple strikes and figure of eight strike was carried out on the pad. The baton was then replaced on the officers' belt.

Figure 5.7 Baton Strikes

Following this with one volunteer acting as a suspect, a prone search and handcuff manoeuvre was carried out. These movements highlighted potential problems with armour moving on the body and compatibility with equipment that officers wear on their belts.

Figure 5.8 Prone search and handcuff

Then with a tackle bag to simulate a possible suspect, the tackle bag was taken and put into the back seat of car. When in place, the tackle bag was moved across the back seat then out of the opposite car door.

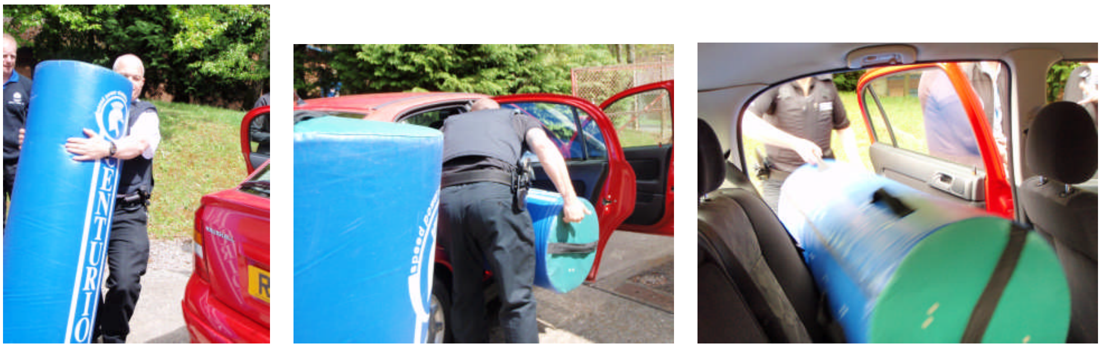


Figure 5.9 Tackle bag movements

5.5.4 Vehicle Evaluation

To evaluate movements in a vehicle, officers were asked to get into the front drivers seat of the car, adjust the seat and put on the seatbelt. Whilst wearing the seatbelt they were then to take an object out of glove box. A member of the trials staff measured the distance the officer was able to reach across the car without feeling restricted. Then the volunteers turned their heads as if reversing the car and were asked to assess how their armour affected general driving movements.

Figure 5.10 Reach in car

5.5.5 Comfort and Fit

After completing these tasks the volunteers were asked to assess the weight of the armour, its size and shape and how well the weight was distributed over the body. Then to consider how the armour interacted (compatibility) with other items of uniform and the Police equipment they wear everyday. They were asked to fill out a questionnaire before they changed into another armour system. However, at the end of the trial when all three armours had been worn they were allowed to amend their ranking if they felt strongly that their views had been changed by wearing another armour system. Only three officers changed their scores and they increased by one mark the marks they had previously given to one armour system.

5.6 Results

The information from the ranking exercise in this trial was not intended to be used as pass/fail criteria. Ranking was only used to highlight the different areas on the body armours where improvements could be made. The aim was to determine if the simple average scoring system could distinguish between the merits of one armour system and another.

Armours 1 (and 4), Chafing:

Armours 1 (and 4) had one male volunteer report a problem with chafing at the neck, six male and four females report problems with chafing at the armhole, one female about the waistband and two female volunteers reported problems at the shoulder. The design of introducing ribbed nylon at the sides was generally not well received and most of the chafing problems at the armhole were due to the nylon sides not fitting closely to the armour panel and not holding the panels firmly enough in place.

Comments:

One volunteer commented that in his opinion this armour was '*The best of the three armours*'. Generally the armour was felt to be light weight and comfortable and many liked the wicking fabric incorporated into the carrier. Some users felt this armour was too bulky at the sides and three would have liked more length on the waistband. Most users did not like the press studs on left shoulder and found them difficult to operate and reach when securing the front panel. They thought them too intricate and fiddly to do up when time was short. They also felt that with use, over time the poppers would get ripped off or just fail. Some volunteers reported that the armour rode up when sitting as illustrated below.

Figure 5.11 Armour 1 (and 4) Armour 'moving up' when sitting in a car

Armour 2, Chafing:

Manufacturer 2 had two male and one female volunteer report problems with chafing at the neck, one male report of a problem with chafing at the armhole, one male about the waistband and male reported a problem at the shoulder.

Comments:

Female officers ranked this armour system very highly with only the one problem at the neck being reported. Most felt it was very comfortable and light weight and it was the favourite of many volunteers hence the high ranking in the trial. The lower cut armholes resulted in comments that there were large gaps which made them feel a bit vulnerable and exposed on the sides. As above, the press studs were felt too be too fiddly and most volunteers would prefer Velcro® type fastenings.

Armour 3, Chafing:

Armour 3 had nineteen volunteers report problems with chafing at the neck, five female and fourteen male, Figure 5.12. Eighteen reports of problems with chafing at the armhole, four female and fourteen male.

Figure 5.12 (a),(b) Collar moving up and 'pinching' at neck and (c) back of armour 'riding up'

One male and one female volunteer reported problems about the waistband and one male and one female reported problem at the shoulder. The design of ribbed nylon under the arms and the close fitting up and around the shoulder was generally not well received and most of the chafing problems at the armhole were due to the softer nylon sides moving up under the arms and pinching most users.

Comments:

This armour had the only comment relating to operational effectiveness. One volunteer had a problem with the lining as it interfered with handcuffs being drawn quickly and resulted in the lining being torn.

Figure 5.13 Armour 3, length of carrier interfering with placement of handcuffs

Most volunteers liked the ‘look’ of this design and thought it would be smart to wear. However, they thought this design was too complicated to put on and adjust Figure 5.5. They also found it too tight around the armholes and didn’t like wearing the higher collar design. Some volunteers complained about chafing at the neck very early in the trial. They found that the design rode up and had a tendency to creep, Figure 5.13. It also hit neck and radio clips when sitting and turning. Generally it was felt to be too bulky and uncomfortable

5.7 Summary

The results in figure 5.14 show that the numerical scoring system was able to highlight a part of an armour where more work needed to be done. From the six armours trialled armour 3 needed most modification and 4, 5 and 6 a little more with armours 1&2 requiring the least modification. It is interesting to note that the average scoring system could also identify types and a difference between females and males within the armour types. Armour 2 was scored high by all females with the scores for the males similar to those for armours 1 and 4. Generally females found the other armours in this trial less comfortable to wear than their male colleagues.

The final analysis of all the scores included how much chafing was caused by the armours. The marks for the amount of discomfort and chafing were significant in ranking the armours in the trial. If there were no problems with chafing, an armour was awarded 4 marks. This mark was reduced by 1 point for any area that had chafed e.g. neck or armhole, shoulder or waist. In the sample size of 30 volunteers, Armour 2 only had 6 (20%), Armour 1 (and 4) had 11 (37%) and Armour 3 had 25 (83%) of volunteers report problems.

Overall both armour 2 and armours 1(and 4) achieved good scores, table 1 and Figure 5.14. The maximum possible score was 128 and armour 2 had an overall score of 98.03, armours 1 (and 4) achieved an equally good score of 93.93 and armour 3 a score of 61.63. The designs of armour 2 and armours 1 (and 4) achieved high scores in all of the tasks as their armour carrier designs allowed plenty of arm movement and moved well on the body. The neck and armholes of these garments were cut much lower than armour 3's carriers and this restricted the movement of the body less.

The standard deviation from the mean values, table 1 were calculated as shown in equation 5.1 and also marked as bars on the chart in Figure 5.14.

$$\sqrt{\frac{\sum (x-\bar{x})^2}{n-1}}$$

Equation 5.1

The values show the level of agreement between the scores awarded by the subjects for the different armours. There was a greater spread of marks for amour 3 which was the armour least preferred by the subjects. The variability in the scores for this armour was shown by a standard deviation of 9.7 when all the subjects' scores are considered. The armour that was consistently awarded high marks and was scored 95.83 by male subjects was armour number 4 with only a variation in scores of 1.2.

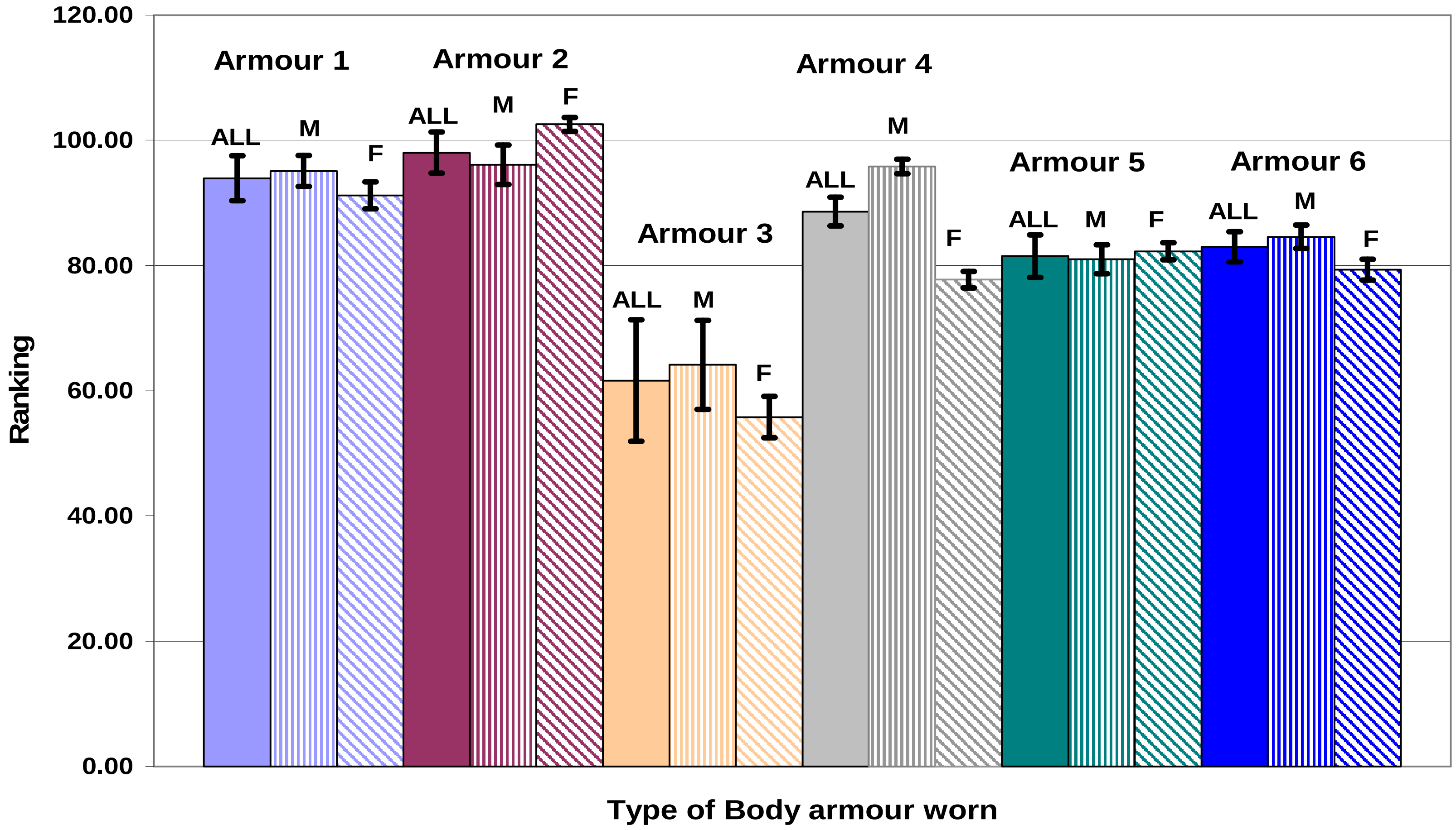


Figure 5.14 Graph of the ranking of the armour systems (bars show standard deviation from mean value)

Table 1 Mean of scores from questionnaire and standard deviation (SD)

Manufacturer	Scores from Ranking					
	All subjects	SD All	Male Subjects	SD male	Female Subjects	SD Female
2	98.03	3.3	96.10	3.2	102.56	1.1
1	93.93	3.6	95.10	2.5	91.22	2.2
4	88.60	2.3	95.83	1.2	77.75	1.3
5	81.50	3.4	81.00	2.3	82.25	1.4
6	83.00	2.4	84.57	1.9	79.33	1.7
3	61.63	9.7	64.14	7.1	55.78	3.3

When comparing the total scores for each activity for three of the armours in the trial, Figure 5.15 illustrates the areas where the armour needed improvement and this data was particularly useful to the manufacturer as a low score indicated exactly which area needed to be improved.

5.9.1 Effect of Reach

The results from measuring the effect the armours had on each subjects' ability to reach the glove box in the vehicle are shown in figure 5.16. This movement depended on the arm length of the individual and tall volunteers with a long reach had no problems with this movement. As some volunteers with a shorter reach stretched across to the glove box they also bent with their back, so it was not a clear arm movement only. Also some volunteers would use their left arm to access the glove box and not their right so found the movement easy. This was reflected in the results which were randomly variable for each individual and there was no clear pattern that one design performed better than another. Generally the reach movement was one which was influenced by the restrictions placed on the neck and armhole area and the amount of chafing caused. The results from this trial were inconclusive and a better method of determining reach needs to be developed.

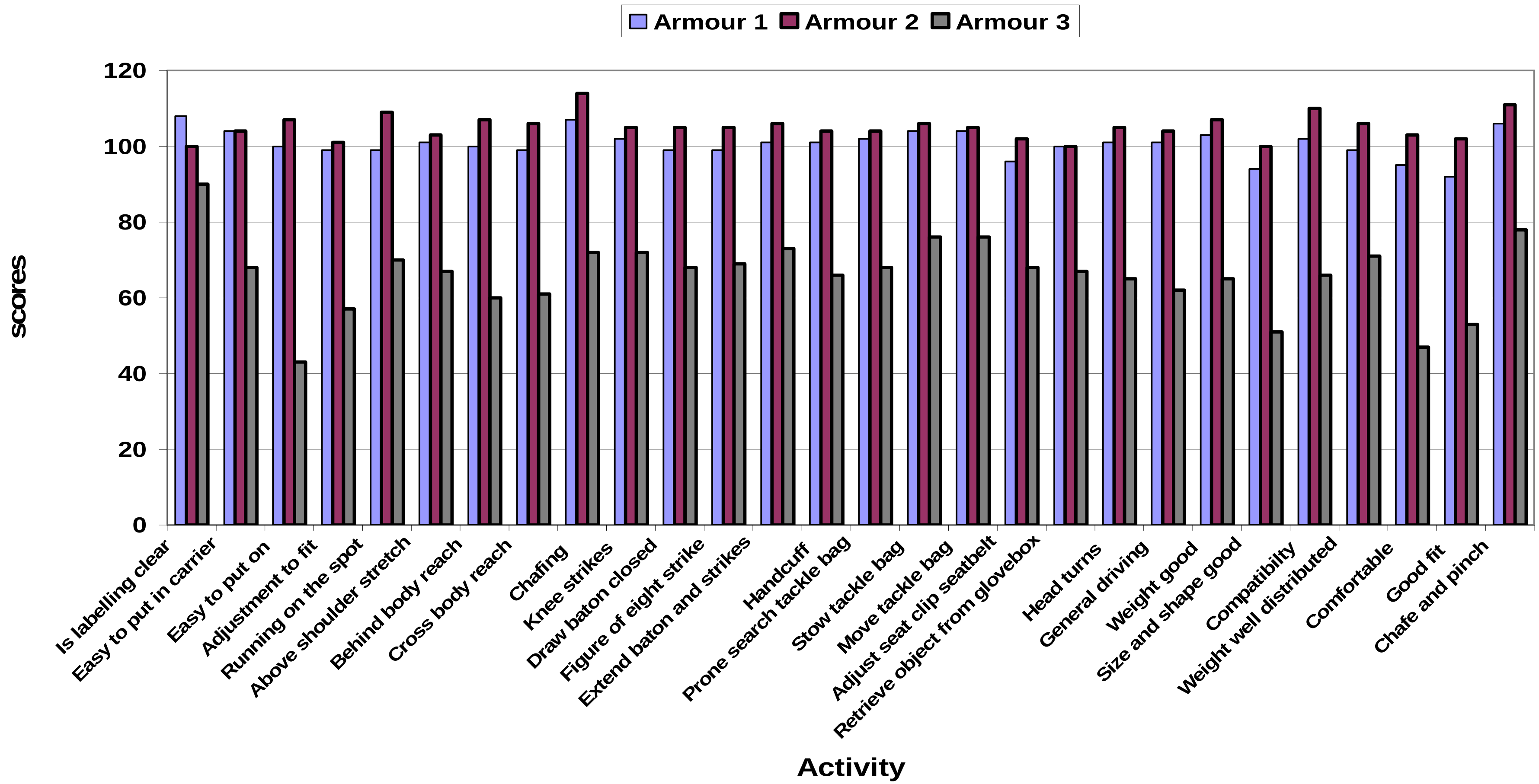


Figure 5.15 Comparison of the totals of 30 volunteers scores for each activity for three of the armours in the trials

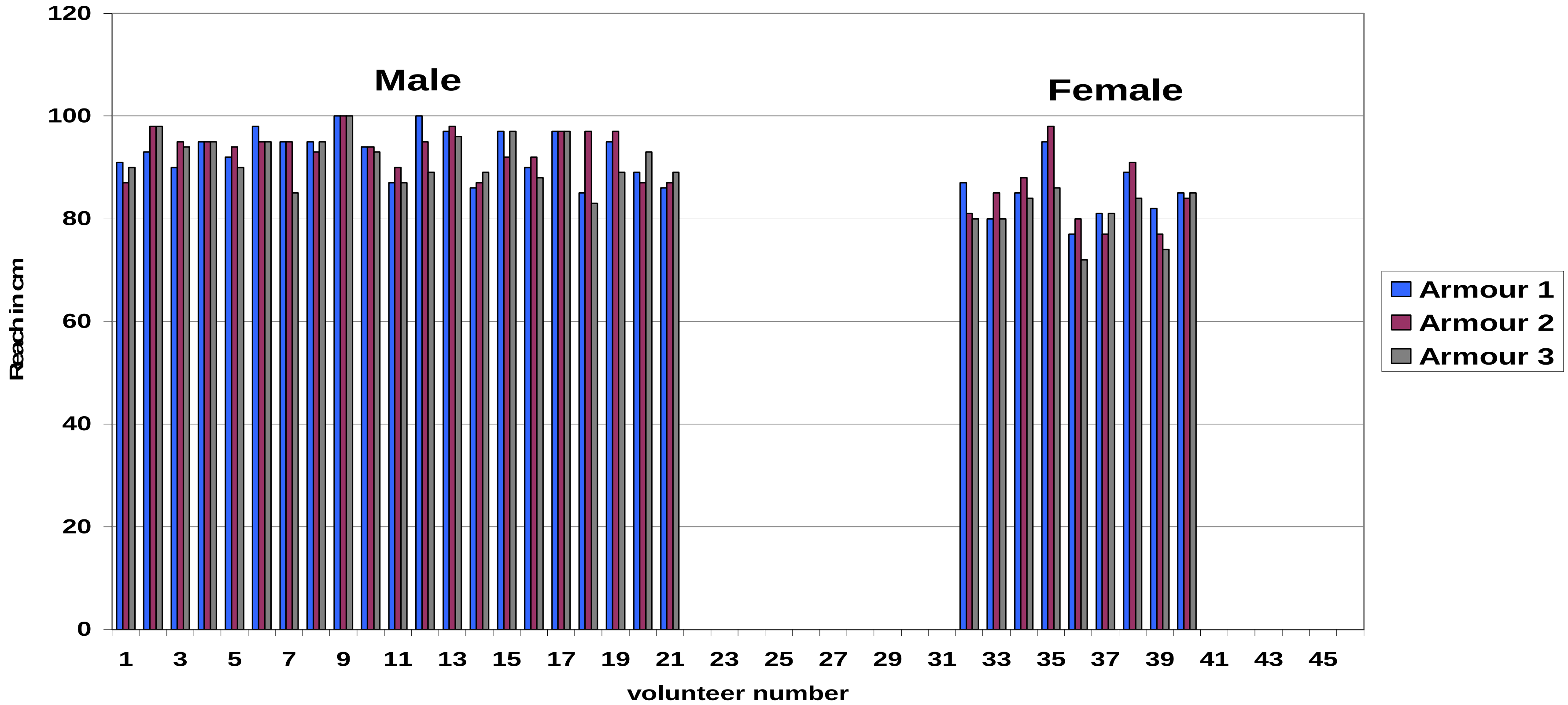


Figure 5.16 Effect of body armour design on the ability to reach in vehicle

5.7.2 Number of subjects

Amours 1, 2 and 3 were trialled with thirty subjects and 4, 5 and 6 with ten subjects. Armours 5 and 6 were the same carriers but with different protective armour panels The results in figure 5.14 show that when the totals were normalised by dividing by the number of subjects. Even when ten subjects are used it was still possible to differentiate between one armour style 4 and another (5 and 6).

The trials described above were successful in highlighting particular areas of the armours where improvements could be made. The questionnaires had been accepted and there was a positive response from the subjects for this type of trial. Valid data was obtained from using ten subjects for a trial.

The author presented the results of this work to the Associated Chief Police Officers (ACPO) body armour group at the National Police Improvement Agency in September 2009.

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Chapter 6 - Flexibility

6.1 Fabric Flexibility

Fabric flexibility and the ability to conform to body shape are parameters that assume great importance for body armour. How flexible a fabric system will be is dependent upon the individual fibres used in the yarns combined with the weave or the structure of the fabric. Most body armours are complex composite items often with many layers of different fabric types incorporating both woven and non-woven fabrics and sometimes metallic structures. The current standard methods for measuring flexibility rely on measuring the flexibility of a single layer of fabric only. The first method of measuring the bending stiffness of a fabric was developed by Pierce[1]. In the Standards ASTM D1388[2] and BS EN 1735[3] the stiffness of a fabric is determined by allowing a 200mm x 25mm±1mm strip of fabric fixed at one end (as a cantilever) to bend under its own weight, Figure 6.1.

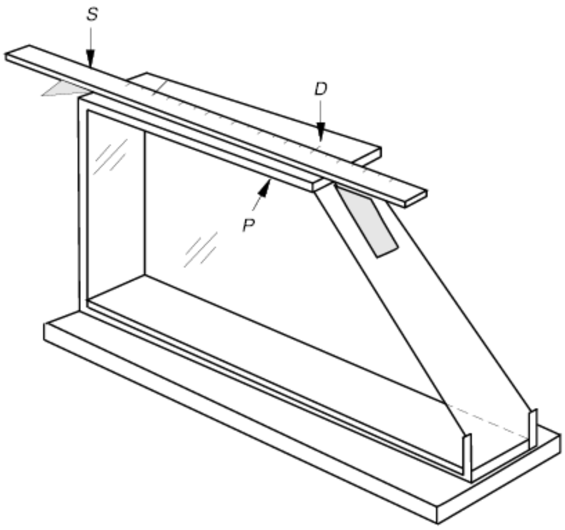

Figure 6.1 Apparatus for measuring bending stiffness of a fabric (as recommended in section 4, of BS EN 1735[3]

The rectangular fabric sample is laid between the platform P and the slide S so that the end of the test specimen is aligned with the zero mark on the slide at point D. The slide is pushed along until the specimen falls over the inclined plane and bends under its own weight. The bending length is measured directly from the rule as the length of the test specimen from the edge of the platform to the zero point on the rule. The test is repeated on five samples and the bending length is the arithmetic mean in centimetres of these five results.

The Heart Loop test method [3]is a very simple method that measures the difference in heights (in millimetres) of a loop of material 600mm long x 100mm wide, as it collapses under its own weight, Figure 6.2. This test is repeated three times in both the longitudinal and transverse directions. The arithmetic mean of the measurements in the six tests is taken as the flexibility measurement which is defined as the lower the loop height, the more flexible the fabric. Due to the thickness and stiffness of an armour system these tests would not be appropriate.

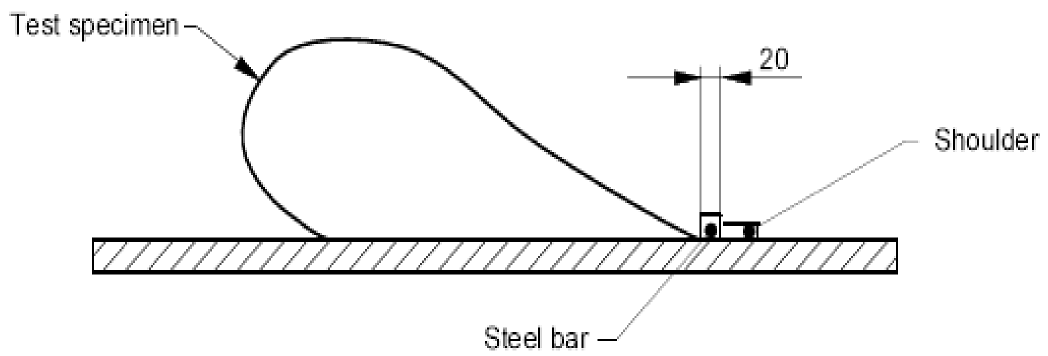

Figure 6.2 Apparatus for Heart loop method of bending stiffness (as recommended in section 3, of BS EN 1735[3]

6.1.1 Drape Coefficient

Drape is defined as the ability of a fabric to bend under its own weight to form folds. BS 5058: 1973[4] describes the Cusick[5,6] method to determine a drape coefficient based on the ability of a circular piece of fabric to fall into folds. A paper template the same size as the fabric is made and weighed to determine its mass (M_1). The fabric sample is placed between two plates, the lower plate has a light bulb attached underneath and the fabric sample is allowed to fall into folds and ‘shade’ this light.

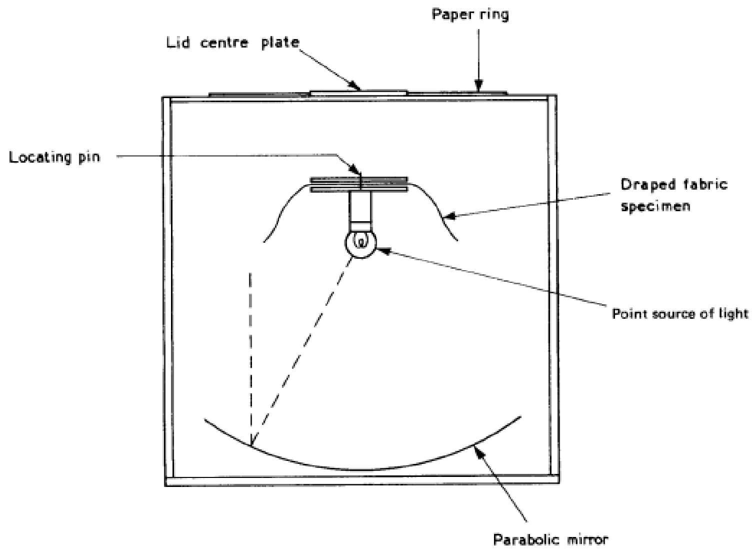

Figure 6.3 Apparatus for measuring drape coefficient of fabric (as recommended in appendix A, of BS 5058[4]

The paper template is placed under the fabric sample and the shadow created is traced onto the paper template. The area of the shadow is cut out of the paper and weighed (M_2). The coefficient of drape is determined from the difference in the masses of the original paper template and the mass of the shadowed area.

$$\frac{M_2 x 100}{M_1}$$

Where: M_1 *= mass of paper ring*

M_2 *= mass of shadow* Equation 6.1

The drape test is a simple and effective way of assessing the drape of a single layer of fabric and many researchers[7,8,9] are suggesting digital imaging and mathematical models as useful modifications to the method. However the major drawback for this work is that most armour panels are too rigid to drape easily in this test.

6.1.2 ASTM Circular Bend Test

ASTM D4032-92[10] is an accepted compression test method for fabrics where one layer of fabric is pushed through a hole in a plate by a circular flat plunger. The maximum force required to push the fabric through the hole indicated the resistance of the fabric to bending. A small scale quasi-static compression test based on ASTM D4032-92 was investigated to determine a methodology that could be used to assess both the flexibility and penetration resistance of typical armour systems. It followed the modified circular bend method described by Missihoun [11] who used four semi-circular probes from 25.4mm – 76.2 mm to push multiple plies of fabric through holes in a plate to measure their bending stiffness. Missihoun had limited success with his experiments due to the the diameter of the probes and the sample sizes being too small. He recommended that further work needed to be done in this area.

6.2 Flexibility Trials on penetration resistant materials

6.2.1 Armour materials

The flexibility and resistance to penetration of several typical armour materials were compared to determine those that would offer the best combination of properties for a body armour system. The criteria for choice of candidate materials were: that the material should be flexible and should also have some knife resistant capability either as a stand-alone system or when combined with a ballistic armour pack. The knife resistant materials used were Kevlar® Correctional [12], and Twaron Stabguard [13]. Two knife resistant armour systems were also used, Armour B which was the woven wire layer from an armour and Armour C a knitted aramid and wire hybrid material. A ballistic aramid pack (pack A) was constructed of 4 layers of Kevlar® 129[12]. 4 layers of Kevlar® Comfort, 2 layers of Kevlar® 129, with an areal density of 4.58Kg/m^2 was used as a base for combined knife and ballistic systems. Another lightweight high strength ballistic material Zylon®[14] poly(p-phenylene-2, 6 benzobisoxazole) was also investigated as was being used for light weight body armour. The weight per unit area kg/m^2 (areal density) of each candidate armour sample was calculated at the beginning of the test.

6.2.1.1 Kevlar® Correctional [12]

This aramid fabric was designed for the protection of Prison Officers[12] (hence the brand name correctional). It is designed to protect against improvised weapons made by prisoners such as sharpened screwdrivers and ice picks. It is woven from a superfine high performance yarn and is a very tightly woven fabric on a 0.3mm pitch with an areal density of 120g/m^2. It is marketed by DuPont as having good spike resistance and it also relies on having an adequate number of layers to prevent penetration.

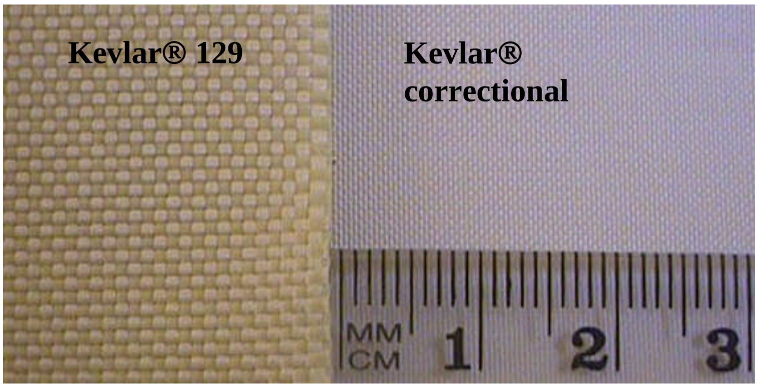

Figure 6.4 Comparison of ballistic Kevlar 129® with Kevlar© Correctional showing the difference in the tightness of the weave.

6.2.1.2 Kevlar® 129 and Kevlar Comfort® [12] Ballistic aramid pack A

A ballistic aramid pack constructed of a sandwich of 4 layers of Kevlar® 129, 24 layers of Kevlar® Comfort (a lightweight knife resistant fabric designed specifically for the police market) and 2 layers of Kevlar® 129 Figure 6.4, with an areal density of 4.576kg/m^2 was used as a base layer for some of the combined knife and ballistic solutions used in the trial. The aramid was woven on a 1mm pitch and the areal density of a single sheet was 200 g/m^2.

6.2.1.3 Twaron Stabguard (Polyethylene (PE) coated aramid)[13]

Stabguard is one of the knife resistant aramids currently available from high performance fabric manufacturer Teijin Twaron, Figure 6.5. The aramid chosen for this investigation had a polyethylene coating. The areal density per single sheet was 256g/m2 and the fabric was woven on a 1mm pitch. As penetration resistance is dependent on having a sufficient number of layers a major disadvantage is that coated fabrics can be bulky and the bulk begins to restrict flexibility.

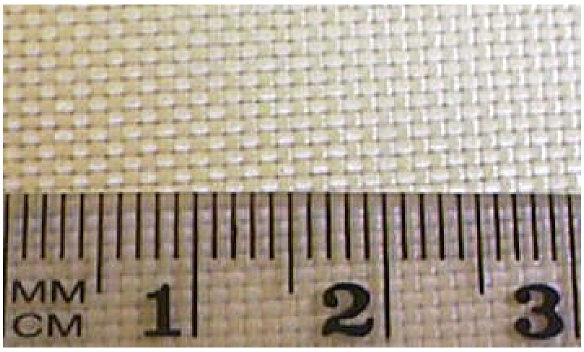

Figure 6.5 Stabguard

6.2.1.4 Fireguard mesh

A coarse mesh similar to those seen in fireguards Figure 6.6 was sourced from an actual armour system primarily for comparison with chain mail systems. This mesh was woven from 12 strand, 0.2mm brass coated wire on a 3mm pitch and the areal density was 1.704kg/m^2.

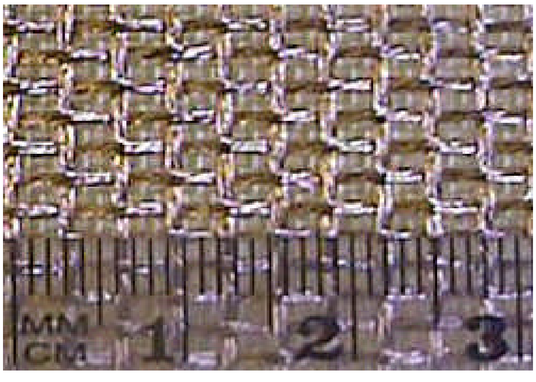

Figure 6.6 Fireguard mesh

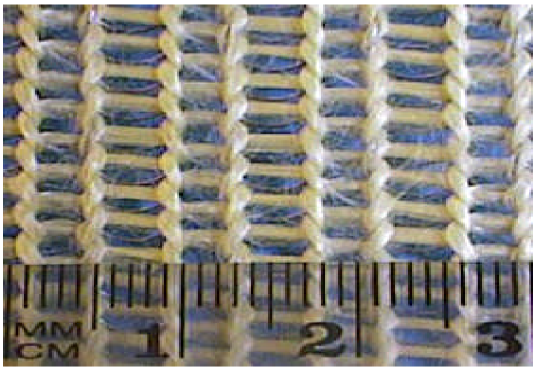

Figure 6.7 Aramid knitted with wire

6.2.1.5 Knitted Wire and Aramid Hybrid

This flexible aramid/wire fabric Figure 6.7 was sourced from an actual armour system. The aramid yarns and wire are knitted together on a 5mm pitch (stitch size) from 0.32mm diameter steel wire and aramid, it had an areal density of 1110g/m^2.

6.2.1.6 Ballistic Zylon®[14]

Zylon® is a high performance fibre which is a PBO fibre (poly(p-phenylene-2,6-benzobisoxazole)). The manufacturer Toyobo[14] claimed that Zylon® has superior tensile strength and modulus when compared with conventional para-aramids. The fabric used in these tests was also woven on a 1mm pitch and had an areal density of 150g/m^2.

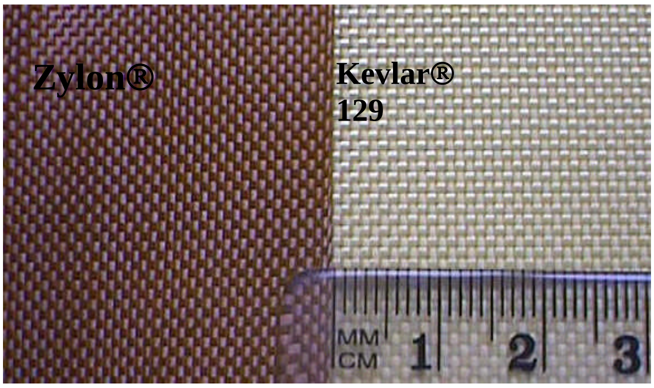

Figure 6.8 Comparison of the pitch of the weave of Zylon® with Kevlar®129

6.3 Quasi-static knife penetration and flexibility tests

The candidate armour materials described above were also evaluated by a quasi-static compression test. An Instron 4208 universal test machine fitted with a 100kg load cell was set up in compression mode. It was fitted with a 20mm diameter hemi-spherical probe to determine the flexibility of the samples, Figure 6.9. For comparison a PSDB S1 blade was chosen as suitable to evaluate penetration resistance this knife is produced to the PSDB specification and is double edged so the penetration on both edges should be uniform [15]. As the standard tests can only measure the properties of one layer, two layers of each of the materials were mounted on a standard PSDB composite test block[16], Figure 6.10 which is a composite lay up of foams and rubber designed to simulate the elastic response of the human torso[16].

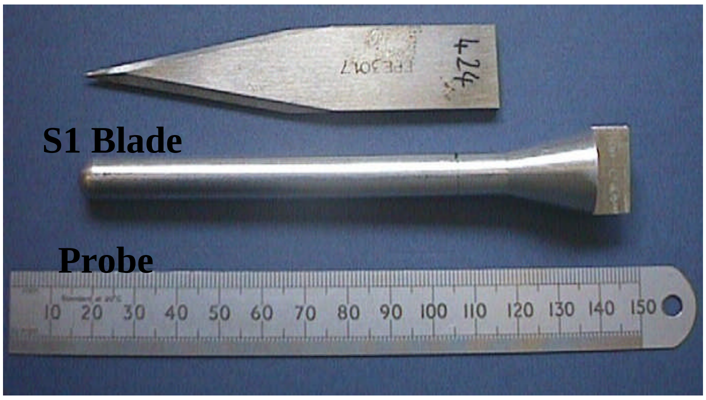

Figure 6.9 Probe and S1 type blade used for the quasi-static tests

Rather than pushing fabric through a hole in a plate as in the ASTM D0432-92 method, backing the armour with the composite test back to simulate the torso may be a more 'realistic' flexibility test for armour. The Instron 4208 machine was set up for a basic compression test so that the maximum allowed displacement in compression was 20mm. The flexibility of each system was evaluated by running the Instron machine at 5mm/minute and compressing the samples 20mm by the probe.

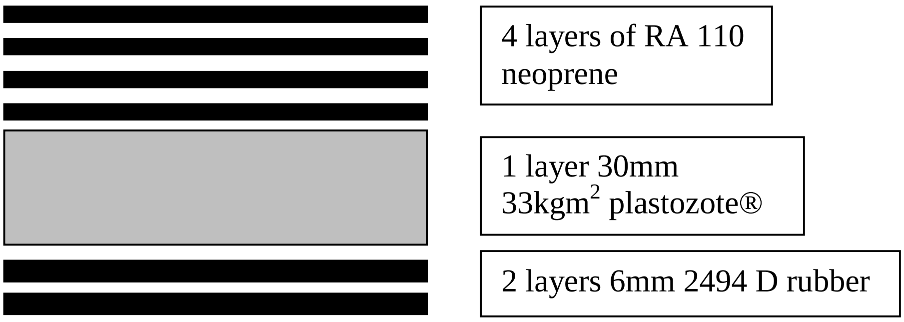

Figure 6.10 Composition of HOSDB composite test block[16]

The resistance to knife penetration of the candidate armour systems was measured over a fixed displacement of 20mm. The results of the measured forces (N) at 20mm from the S1 blade were compared with those of the probe. The materials tested could then be compared according to their penetration resistance and flexibility.

6.3.1 Results

When the PSDB composite block only, was compressed with the probe a resistive load of 134.8 N was recorded at 20mm, similar results were obtained with 2 layers of Ballistic Kevlar® 129 and 2 layers of Kevlar® correctional. Zylon® was a less flexible with a recorded load of 164.0N. The 2 layers of PE coated aramid recorded a load of 251N and this fabric was less flexible than the previous two Kevlar® products. The fireguard mesh and the aramid and wire samples were very inflexible and had resistive loads of 328N and 393N respectively, Table 6.1.

Table 6.1 Comparison of Flexibility and Penetration resistance of candidate armour materials.

Material type	Areal density (kg/m^2)/layer	Force at 20mm of displacement	
		S1 Blade Force (N)	Probe Force (N)
PSDB composite backing only		30.9	134.8
2 layers PE coated aramid	0.512 (0.256 per layer)	104.4	251.2
2 layers Ballistic Kevlar® 129	0.4 (0.2 per layer)	38.4	139.3
2 layers Zylon®	0.3 (0.15 per layer)	25.2	164.0
2 layers Kevlar® correctional	0.24 (0.12 per layer)	56.9	138.6
Fireguard mesh	1.704 (per layer)	135.8	328.6
2 layers knitted aramid & wire	2.22 (1.11 per layer)	99.0	393.0

The results from the penetrative test showed that the materials behaved as expected under a point load. When the forces are concentrated at the tip of the blade, high stresses are generated and all the test samples were perforated. The two ballistic only test samples Kevlar 29® and Zylon® had little resistance to perforation at resistive loads of 38N and 25N respectively. Kevlar® correctional was more resistive to penetration than the ballistic only test samples at a penetrative load of 56.9N. At 104.4N the PE coated aramid was more resistant to penetration than Kevlar 129®. The results from the knitted aramid and wire were 99N which was comparable to the PE coated aramid. At 135.8 the fireguard material was most the resistive to penetration. The low value of 99N to perforate the knitted aramid and wire sample was due to the increase in cross-sectional area of the blade forcing the knit stitch open allowing the blade to penetrate.

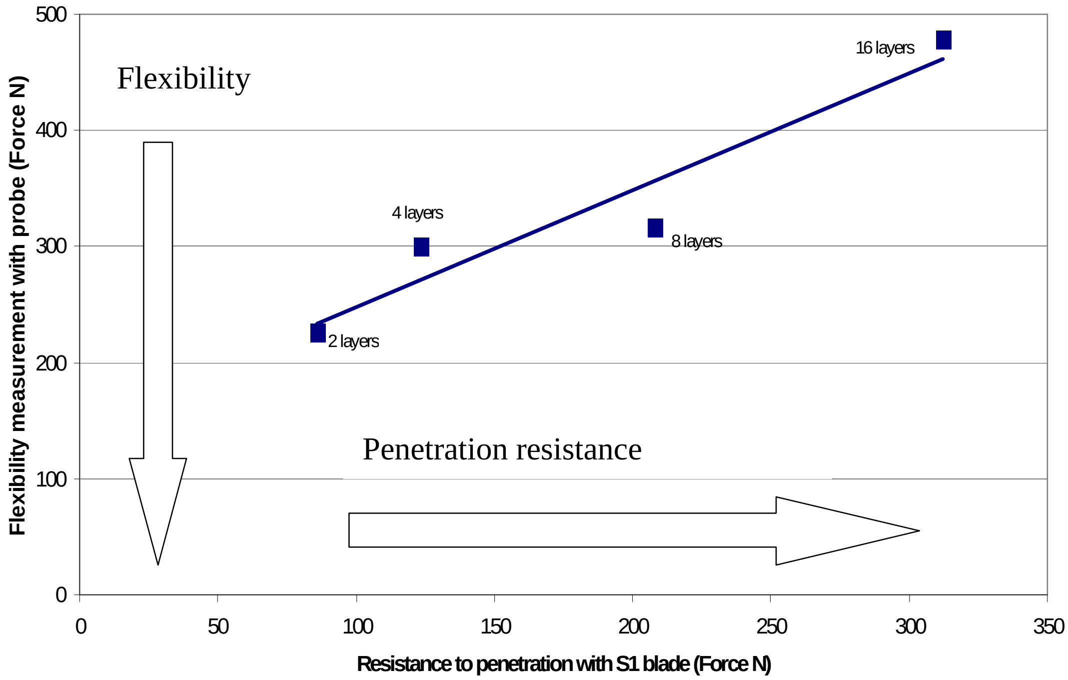

Figure 6.11 Effect on flexibility of increasing the number of layers of a polymer coated aramid

The effect of increasing the number of layers (in increments of 2 layers) from 2 to 16 layers of a polymer coated aramid fabric was further investigated by performing a number of quasi-static tests as described above using the probe and the S1 blade.

Figure 6.11 shows that as the number of layers increase flexibility decreases and penetration resistance increases.

6.4 Mechanical Flexibility test

A more appropriate test method for determining flexibility for amour is the mechanical flexibility test as described by Horsfall and Watson [17]. As in ASTM D0432- 92 it is a simple mechanical test based on a plunger pushing the armour through a circular hole in a plate to force bending/distortion in two directions simultaneously. It was found to be an effective method of determining the flexibility of an armour panel. The differences were that both the hole in the plate and the probe were much larger to allow a sample size relative to a whole armour panel to be tested. The plate was 25mm thick and the sides of the hole had a radius of 12mm, so that the panel was fed smoothly and did not snag as it was forced into the hole, Figure 6.12.

Figure 6.12 (Left) Support plate with 200mm diameter hole. (Right)The 100mm hemi-spherical probe

An annular steel weight of 7.85kg with an inner radius of 250mm was placed on the armour to prevent folding. A hemi-spherically ended probe of 100mm diameter was then used to force the armour into the hole in the plate. The test uses a Zwick 1484 universal tension/compression test machine fitted with a 200kN load cell and set up in compression mode.

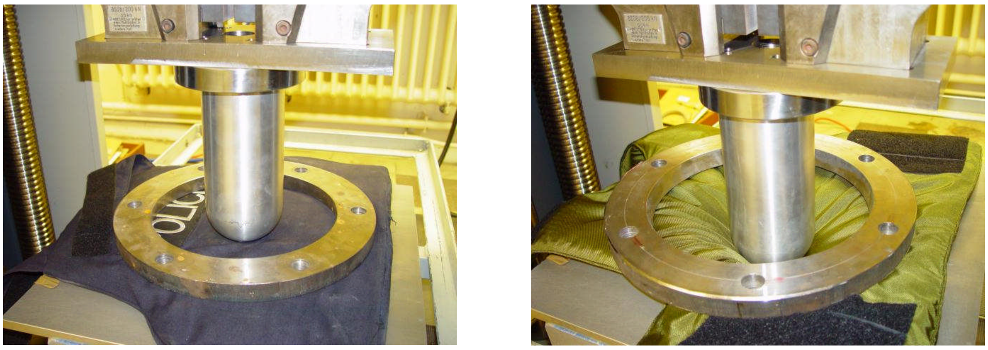

Figure 6.13 Flexibility test setup showing end position of probe after 250N load applied (left) Stiff armour and (right) flexible armour

The machine speed was 5mm per minute until a maximum load of 250 N or 50mm of displacement of the probe had been reached. This test gives a profile of the load on the armour against the distance moved by the armour whilst conforming to the shape of the plunger, Data were captured as load/ displacement graph and stored in a proprietary format then exported as an MsExcel file. In the original work, the mechanical flexibility test was used to provide a fully quantitative measure of flexibility on four different ballistic and knife resistant body armour types listed in Table 6.2 below.

Table 6.2 Body armour types and protection level offered.

Armour code	Construction Details	HOSDB Protection Level [15]
A	1 layer chain mail, 26 layers of coated aramid	HG1A-KR2
B	Quilted composite pack - 40 layers of fine weave and polymer coated aramids	HG1A-KR1
C	3 quilted packs of aramid	HG1-KR42
D	1 layer chain mail 33 layers PBO fabric	HG1A-KR2

The armours used varied from armour D, an older style stiff, body armour system HG2-KR42 to armour A, a more flexible body armour system. Generally the knife resistance layer of polymer coated aramid systems tend to make the armour panel more rigid armour than chain mail systems. The results of these objective tests were then compared to a second set of subjective trials in which the flexibility of the same armour was assessed by subjects manually flexing the armour and ranking its flexibility.

6.4.1 Results

The data from the four armours tested are shown in Table 6.3 showing that armour A was the most flexible with 46.51 mm of displacement at the maximum load of 250N. The HG2+KR42 armour C was the least flexible panel at 7.95mm for a maximum load of 250N it had the lowest amount of displacement. The flexibility results from armours B and D 15.45mm and 25.29mm respectively were between these two values and correlated with the ranking results from the manual selection trial, described below and in table Table 6.4.

Table 6.3 Mechanical flexibility test results

Armour No.	Max Load (N)	Displacement at Max Load (mm)
A	250.06	46.51
B	250.68	15.45
C	249.97	7.95
D	249.97	25.29

6.5 Manual Flexibility

A manual and purely subjective test of flexibility for comparison with the mechanical test was carried out. Four laboratory workers from the Home Office Scientific Development Branch body armour test house who were experienced in handling body armour ‘flexed’ each of the armours, then ranked them in order of flexibility. The flexibility of these panels was determined manually by bending and flexing the armours, and assessing their ability to fold in a concertina-like manner from the top to bottom of a front panel. These testers did not know the results of the mechanical trial described above. The results of this subjective ranking are included Table 6.4, with the construction details and level of protection offered by each armour system. Table

6.4 compares the four armours in terms of both the manual subjective “feel” test and the mechanical flexibility test.

Table 6.4 Comparison of machine/manually assessed flexibility tests

Armour code	Manual Ranking and perceived Flexibility	Machine Ranking	HOSDB Protection Level[15]
A	1st Most flexible	1	HG1A-KR2
D	2nd Flexible	2	HG1A-KR2
B	3rd Flexible	3	HG1A-KR1
C	4th Least Flexible	4	HG1-KR42

The results show that the mechanical flexibility ranking achieved by using a compression test machine concurs with the ranking achieved through subjective comparison by experienced personnel. The subjective test gives good results but is obviously only a comparative test between body armour samples on a given day. It relies purely on the technical ability of the testers to distinguish between samples and to rank them. The mechanical flexibility test allows a fully quantitative measure of flexibility to be achieved which can then be compared to previous data.

6.6 Body Armour Flexibility Trial for the Metropolitan Police

The mechanical flexibility test was investigated further as part of the work for the National Police Improvement Agency assessment of body armour. The Metropolitan Police Physical Protection Group provided eight samples of body armour manufactured by four different suppliers for the trial to assess their relative flexibility. Each manufacturer supplied two samples as 400mm x 400mm square panels so that a direct comparison of the flexibility of each panel could be determined without the influence of any shape effects that might be seen in testing of a shaped front or back armour panel. The previous work had used the actual panels from body armours so there was some small variation between the shapes of the test panels. Each armour sample was placed flat on a plate with the body side of the armour upwards and then the probe was lowered to contact the body side face of the armour Figure 6.14.

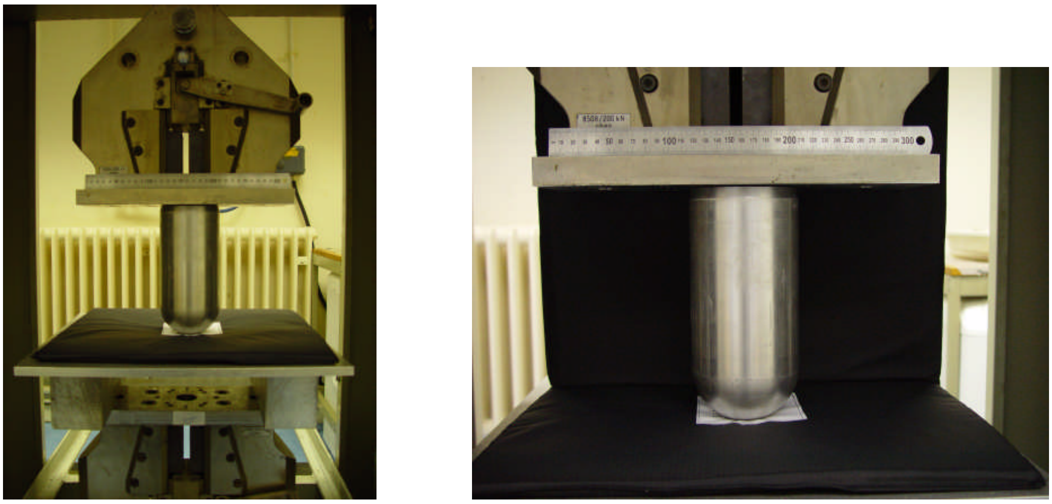

Figure 6.14 Flexibility test set up for armour panels

This was to achieve bending in the same orientation as if the armour was being worn next to the body. As body armour is not tightly restrained on the human body when it is worn for these tests the retaining ring was not placed on the top surface to restrain the armour. So the downward movement of the armour was not restricted. This would determine whether the armour system was flexible enough to fold over as it was pushed through the hole in the plate. Three flexibility tests on each panel were carried out and data from each test were exported to MsExcel. The data from each test were plotted graphically as load in newtons (N) versus displacement in mm.

6.6.1 Flexibility Trial Results

Each manufacturer had provided two panels so for ease of comparison the trial results from both panels were plotted on one graph.

Armours E and F

There was good correlation between each of the three tests on each sample. Sample F was less flexible as can be seen in Figure 6.15. Where the resistance to flexure is shown by a steeper rise to the maximum load of 250N being reached in approximately 30mm. Between 20 and 30mm of displacement the loads increase steeply to the maximum at 250N as the panel does not bend. In comparison as shown in Table 6.5, Sample E was more flexible and the peak load was not reached before the maximum allowed displacement of 50mm.

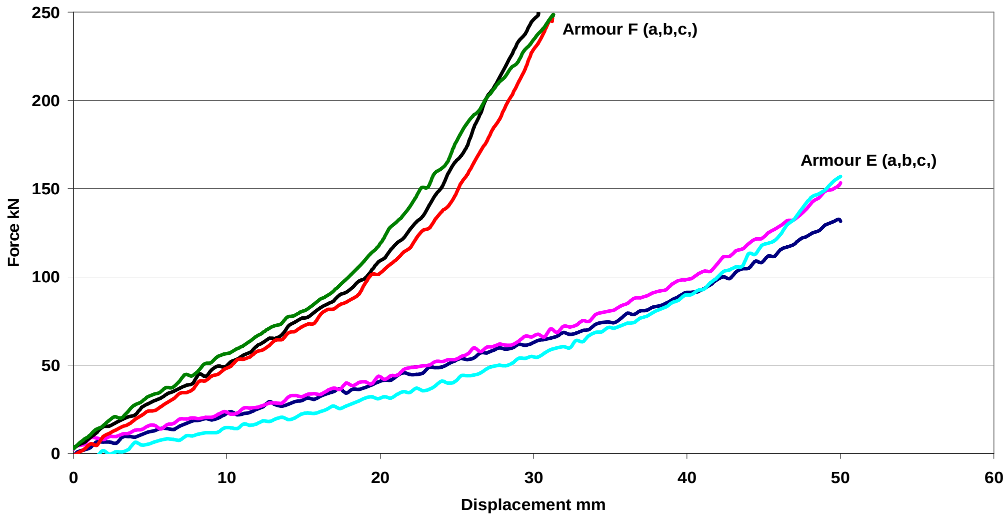

Figure 6.15. Comparison of flexibility of armours E and F

Table 6.5 Comparison of peak force and displacement of armours E and F

Armour type	Test number	Peak force N	Displacement mm
F	A	250	31
	B	250	31
	C	250	30
E	A	132	50
	B	154	50
	C	157	50

Flexibility trial – G and H

All tests showed that these panels could be displaced 50mm without the maximum load being reached, Figure 6.16. Sample G was less flexible slightly as can be seen in the Figure 6.16, where the resistance to flexure is shown by the higher average peak load 190N being reached in 50mm.

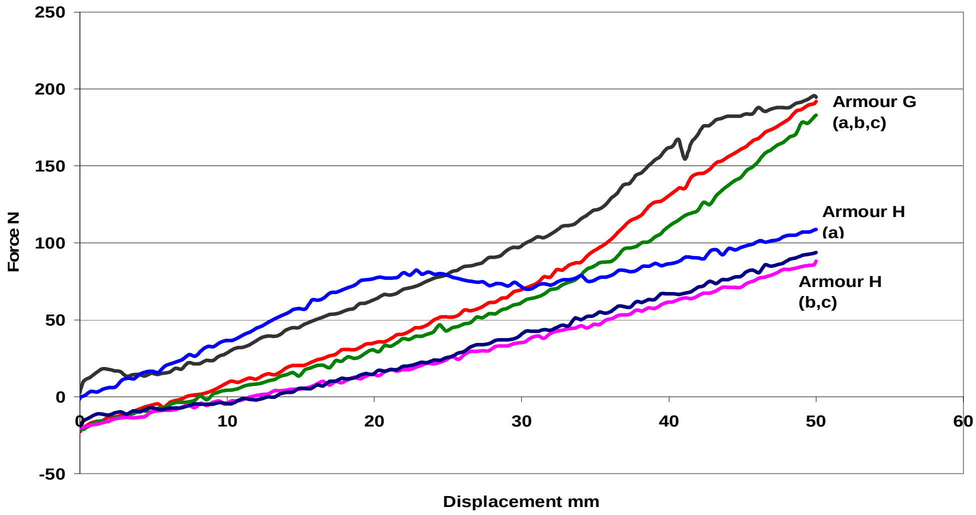

Figure 6.16 Comparison of flexibility of armours G and H

In comparison Sample H was more flexible with an average peak load of 100N to reach 50mm, Figure 6.16. It was interesting to observe that the first test on each series started on a completely flat panel at zero displacement. The first test on this panel shows a rise in load to 82N at about 23mm of displacement where the panel starts to fold around the probe then the load falls as the panel conforms to the shape of the probe and slips through the hole in the plate. After the first test on these panels they could not be returned to complete flatness and as can be seen in the plots there was about 7-8mm of 'sag' on the second and third tests.

Table 6.6 Comparison of peak force and displacement of armours G and H

Armour type	Test number	Peak force N	Displacement mm
G	A	195	50
	B	192	50
	C	183	50
H	A	109	50
	B	88	50
	C	94	50

Adding the negative 'sag' values to the final loads would bring the maximum load values in closer agreement. However, 'sag' is a real effect and indicates that armour has been deformed by the probe. This indicates that as with clothing, once an armour has been worn it conforms to the body shape of the wearer and it retains that shape, which is a positive result for comfort and wearability.

Flexibility trial –I and J

The two solutions I and J were both very flexible and there was also good correlation between the three tests on sample J. This panel was very flexible and could be displaced 50mm by an average load of 122N, Figure 6.17. Sample I began to flex in a similar fashion until about 10mm, where the resistance to flexure seems to climb rapidly with a peak at a load of 160N being reached in approximately 30mm. This is illustrated in

Figure 6.18 showing the panel being flexible enough so that folds were able to form and these folds restricted the armour moving smoothly through the plate which caused the loads to rise in a non-uniform manner in this case.

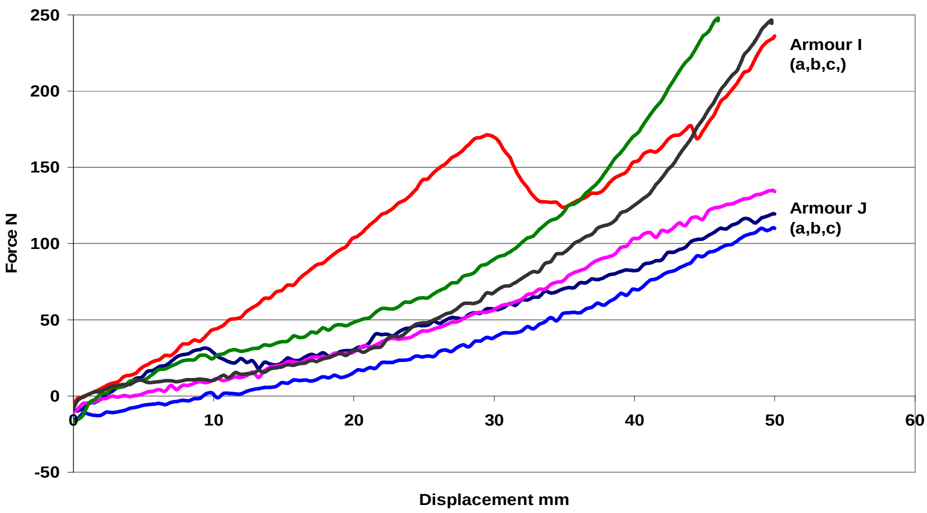

Figure 6.17 Comparison of flexibility of armours I and J

Figure 6.18 Flexibility of armour panel I showing folds developing and maximum displacement of the armour through the plate

The flexibility of panel I allowed folds to form in the second and third test and the maximum load was reached at the maximum allowed displacement,
Figure 6.18. It was again observed that the first test on each series started on a completely flat panel at zero distance. However after the first test the panels could not be returned to complete flatness and as can be seen in the plots there was some ‘sag’ on these tests. Adding the negative ‘sag’ values to the final loads would bring the maximum load values in closer agreement but as this armour was very flexible it is likely that as above this is a real effect showing conformability

Table 6.7 Comparison of peak force and displacement of armours J and I

Armour type	**Test number**	**Peak force N**	**Displacement mm**
J	A	119	50
	B	134	50
	C	110	50
I	A	236	50
	B	245	50
	C	244	50

Flexibility trial of armours K and L

Panel K was more flexible than panel L, Table 6.8 and could be displaced 50mm at an average load of 170N. Sample L flexed less as can be seen in Figure 6.19 where the resistance to flexure is shown by the maximum peak load being reached in approximately 32mm. It was also observed that as in the tests on the more flexible panels above the first test on sample K started on a completely flat panel at zero distance. However after the first test the panel could not be returned to complete flatness and as can be seen in the plots there was about 3-4mm of 'sag'. The first test on panel K also shows higher loads in the initial part of the curve, after being flexed however it was less resistant to flexure in the second and third tests.

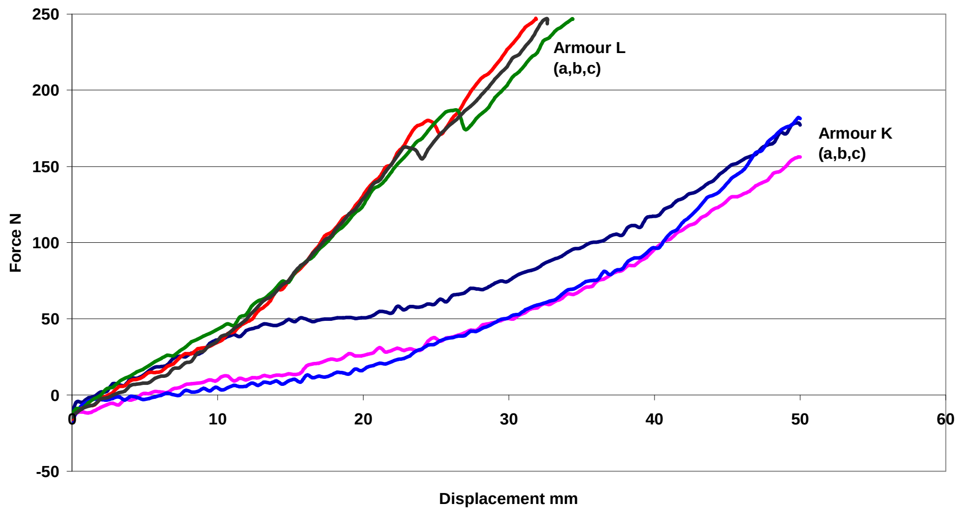

Figure 6.19 Comparison of flexibility of armours K and L

Table 6.8 Comparison of peak force and displacement of armours K and L

Armour type	Test number	Peak force N	Displacement mm
K	A	177	50
	B	156	50
	C	181	50
L	A	250	33
	B	250	32
	C	250	34

6.7 Summary

Each armour test sample was tested three times and the results above show there was good repeatability from the mechanical flexibility test. An interesting observation in the second and third of the tests on the most flexible armours was that the first test on each series started with a completely flat panel and the machine set at zero distance. After the first test the panels could not be returned to complete flatness and when the machine was returned to its original starting point the panels continued to ‘sag’. There was up to about 7-8mm of ‘sag’ on these tests. This had not been seen in the earlier tests when the retaining ring had been used. With the retaining ring in place it is relatively straightforward to stretch the panel until the test area is taut again and to return the machine to zero at its original starting point. Without the retaining ring the flexible panels sagged into the hole showing that after conforming to the shape of the probe these panels were exhibiting some ability to drape. The retaining ring provides a more standardized test as it prevents the panels slipping and folding.

The tests include the effect of ‘sag. Adding the negative ‘sag’ values to the final loads when the data is processed would bring the maximum load values in closer agreement. However, the ‘sag’ was a real effect and indicates that once a flexible armour has been worn, it begins to conform to body shape and it retains some of that shape after wear (similar to wear with shoes) which is a positive result for the comfort and wearability of armour. When armour is worn on the body the user is instructed to adjust the armour ‘to fit’ using the body belts and side fastenings.

The probe results show that flexibility reduces with stiffness. The tradeoff in armour terms is that the number of layers necessary to prevent penetration results in a thicker vest and increasing the number of layers reduces the flexibility of the system. The compression test with the small probe did indicate how flexible the panels were but the small cross-sectional area of the probe may not compress sufficient fabric to replicate how the armour might behave when compressed on a body. The trials have shown that measurements from the mechanical flexibility test give a good quantitative data of the flexibility of an armour panel.

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Chapter 7. Reliability of body armour performance

Part 1. Evaluation of the reliability of ceramic plate armour

7.1 Introduction

The aim of this part of the study was to determine the reliability of ceramic armour plates and soft body armours to achieve the same ballistic performance level after time. The performance of most armour is evaluated when it is proof tested against a standard as a new item. Early aramid fibres were known to be sensitive to water and they were also susceptible to degradation by UV light [1,2,3]. So the aramid armour panel was often encapsulated in a protective waterproof cover. However if the waterproof cover becomes torn there was some concern that water vapour and sweat could permeate an armour panel and degrade its performance. Ceramic armour plates are worn in front of soft armour as protection against rifle rounds. The exact composition and construction of the of the armour plates in this trial was commercial in confidence. However generically, a rifle plate consists of a ceramic tile bonded onto a backing and is usually covered in a strong polycotton cover. It is possible that damage through handling, ageing or deterioration in use, could result in cracking of the ceramic face of an armour plate or de-bonding of the composite backing. This damage would be invisible to the user but the performance of the armour plate might be affected. This study will examine the effect of batch to batch variation, deterioration, ageing effects and induced damage on ceramic armour plates and the degradation of textile armours due to the absorption of water.

7.2 Evaluation of the ballistic performance of ceramic armour plates

The UK/SC/4898[4] specification is a proof test to confirm that the plates used for this trial stopped the designated ammunition at a specified velocity. However, to evaluate the performance of one plate against another, in this work a V_{50} method was used [4] where the velocity at which the plates are perforated is determined. In this work perforation was defined as: when any part of the ammunition fired, was visible at the back surface of the armour plate. The V_{50} is defined as the velocity at which 50% of the shots fired are stopped by the armour. It is the mean of six 6 shots, (three stops and three perforations). The range (spread) of velocities allowed for a six shot V_{50} is $40ms^{-1}$ between the lowest recorded velocity for a perforation and the highest velocity recorded for a stop [5]. The velocity /perforation data was analysed by a logical regression method in order to predict the probability of failure and confidence limits. The model also extrapolated the data in order to predict the associated confidence levels at which the failure probability was less than 5% (V_{05}) i.e. that 95% of the shots will be stopped by the armour.

For this trial three V_{50} ballistic tests were carried out with the specified ammunition and at the specified range on each of six different batches of plates, representing 12 years of production. All the V_{50} tests in the trial were against plates supported by soft body armour which was strapped onto a conditioned Plastilina® backing[6] with one shot aimed at the centre of each plate tested. All plates were X-rayed before the ballistic test to ensure that they had no cracks. Sufficient shots were fired on batches 3 & 4 so that three V_{50}'s on ''as new'' condition armour plates were obtained,.

To study the effect of cracks a number of plates from the most recent production years (batches 1&2) were 'pre-cracked' in a hydraulic press. Sufficient load was applied until the plate cracked (a distinct noise indicated this happening). They were then checked visually and there were no clear signs of damage at the surface. These plates were X-rayed to show the positions of the cracks.

The X- rayed plates showed definite severe cracking in all cases, a typical example of an armour plate showing induced pre-cracks and shot position is shown in Figure 7.1. For the tests the X-ray's were scaled 1:1 with the plates so the X-rays could be used as a template to transfer the pattern of the cracks and mark up each of the test plates, Figure 7.3.

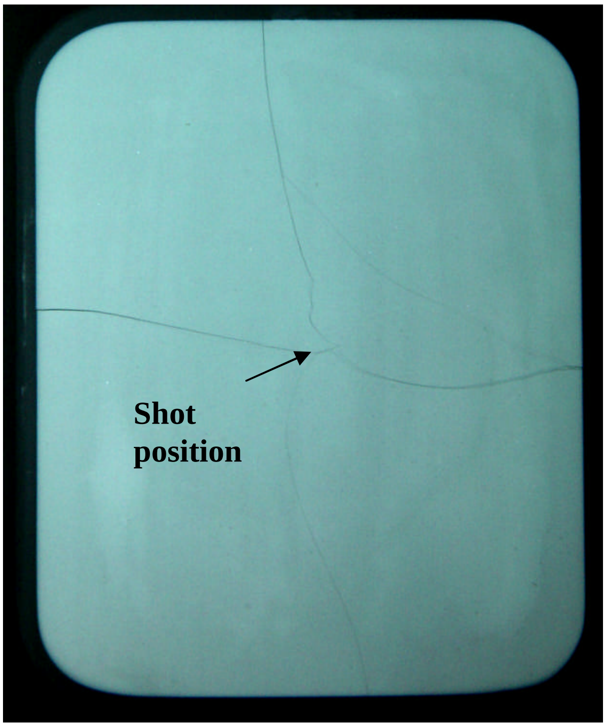

Figure 7.1 X-rayed Armour plate showing induced pre-cracks and shot position

Three V_{50} ballistic trials were performed on these pre-cracked plates with the shot position aimed at the area of the plate with the most cracks Figure 7.2.

Figure 7.2 Ceramic plate showing bullet just before impact (left) and impact on plate right

Figure 7.3 Examples of cracked plates (after test) showing transfer pattern of crack markings and shot aiming positions.

Following this trial, batches of plates from earlier production years were X-rayed before V_{50} ballistic testing to confirm the condition of the plates. The majority of plates classified ‘as new’ from these batches showed no evidence of either severe or hairline cracks. However the X- ray examination confirmed that a small proportion of the oldest plates (batches 5 and 6) had some very small cracks and that these were difficult to detect when visually inspected These plates were separated from ‘as new’ condition plates and a V_{50} obtained for each, see batches 5 & 6, and Table 7.1.

It was found that all batches of plates assessed as being in ‘as new’ condition exceeded the ballistic specification by at least 15%. Figure7.4 shows the performance of these batches was 16% to 24% above the limit specified.

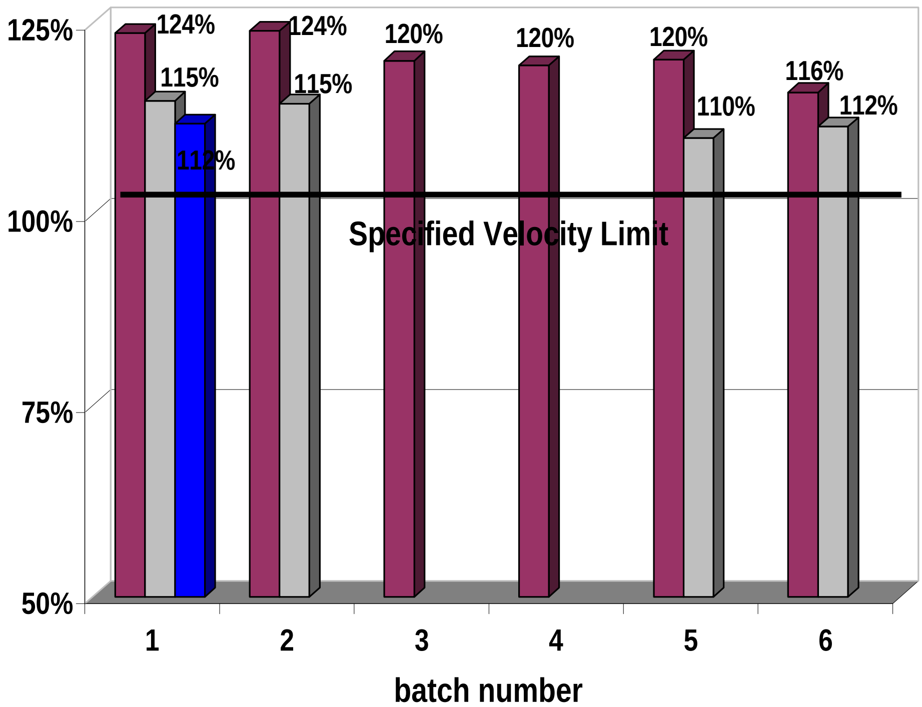

Figure7.4 Comparison of V_{50} velocity (%) for allbatches of plates in 'as new' (purple), 'cracked' (grey) and reject (blue), conditions against specified proof test velocity limit.

The results showed that the plates with very fine cracks still performed 10-12% above the specification, but had a 4-10% reduction in V_{50} when compared to ''as new'' condition. Pre-cracked plates performed 15% above the specification with a 7-8% reduction in the mean V_{50} performance of each batch of pre-cracked plates compared with 'as new' condition. The damaged areas of a batch of plates that had been classified as rejects and exhibiting clearly visible damage were also tested. These plates also performed 12% above the specified performance level. A statistical analysis of all the plates in the trial was carried out on the data, to enable the prediction of levels of confidence, based on the variability in performance against perforation and variations due to batch type.

Table 7.1 Effect of cracking on V_{50} trial results

Batch number	Plate Condition	Performance above specification (%)	% change in mean V_{50} ms^{-1} ''as new'' compared with cracked
1	'as new'	24%	
	'pre-cracked'	15%	-7.2%
2	'as new'	24%	
	'pre-cracked'	15%	-7.7%
5	'as new'	20%	
	cracks detected by X-ray	10%	-8.5%
6	'as new'	16%	
	cracks detected by X-ray	12%	-3.9%
Reject plates	Damage clearly visible	12%	

7.3 Statistical Model of plate data

A statistical approach by Ringrose[7] was used to model the behaviour of the plates and to provide statistically reliable data on the V_{50} and proof velocity. The analysis used the standard statistical method of a linear model (also referred to as logistic regression). This allows probabilities to be predicted as a function of a set of input variables which can then be used to estimate and produce a confidence interval for the V_{50}, V_{05} and V_{95} [8,9,10]. Figure 7.5 shows a graphical representation of the probability of perforation as a function of normalised velocity for all the plate batches, with the normalised specified velocity limit equal to 1. From these curves it is possible to read the velocity at any specified probability of perforation failure. It was found that the statistical model of plate performance gave a graphical output comparable to the Critical Perforation Analysis (CPA) proposed by Gotts *et al*[11]

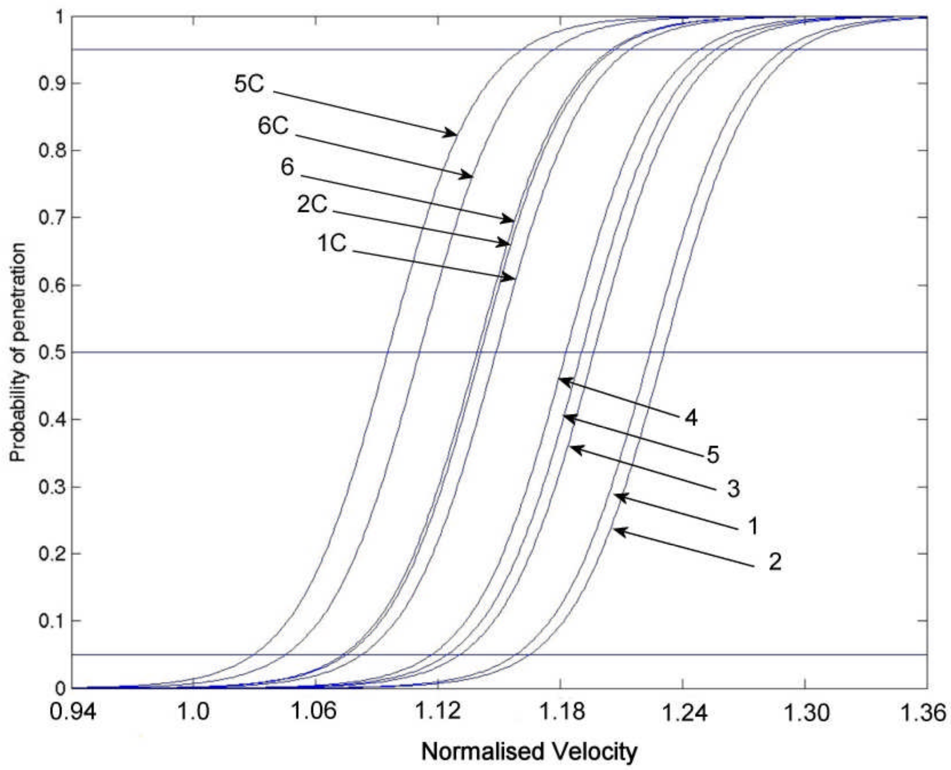

Figure 7.5 Fitted models of probability of perforation vs velocity normalised with the specified velocity limit, equal to 1

The data was tabulated in table 7.2 to illustrate the confidence limits for V_{50}, V_{05} and $V_{95,}$ Table 7.2. For this work the V_{05} is important as it predicts the velocity at which there is only a 5% chance of perforation. It can be seen that for all tile batches, cracked or ''as new'' the V_{05} is above the upper limit of the proof velocity. However, it must be emphasized that the V_{05} and V_{95} are extrapolations from the test data as the data set was collected from velocities fired close to the V_{50}. Consequently the confidence limits on the V_{05} are relatively large. The 95% confidence limits (i.e. the range within which we are 95% certain the true value lies) are tabulated for V_{05}, V_{50} and V_{95}. It can be seen that the V_{05} values all lie above the proof test velocity. However, in the case of batch 6C the 95% confidence level in the lower limit for V_{05} falls slightly below the proof test velocity. Therefore, the model predicts that it is not possible to have 95% confidence that there would only be a reasonably small (5%) chance that perforation would occur. However this result is based on only 6 shots on one batch of armour so in reality this represents a very small chance of failure.

Table 7.2 Confidence limits for the values of calculated V_{05}, V_{50} and V_{95} ms^{-1}

Batch No C = cracked		V_{05} and 95% Confidence limits			V_{50} and 95% Confidence limits			V_{95} and 95% Confidence limits		
	n	Lower limit	V_{05}	Upper Limit	Lower limit	V_{50}	Upper Limit	Lower limit	V_{95}	Upper Limit
6C	6	0.98	1.05	1.09	1.07	1.12	1.16	1.14	1.18	1.25
6	18	1.01.	1.08	1.11	1.11	1.15	1.17	1.19	1.21	1.26
5C	7	0.96	1.03	1.07	1.06	1.10	1.14	1.13	1.17	1.23
5	15	1.07	1.13	1.16	1.17	1.20	1.23	1.24	1.27	1.33
4	8	1.05	1.10	1.16	1.15	1.19	1.23	1.22	1.26	1.32
3	23	1.08	1.14	1.16	1.18	1.21	1.23	1.25	1.27	1.33
1C	21	1.03	1.09	1.12	1.13	1.16	1.18	1.19	1.22	1.28
1	21	1.11	1.17	1.19	1.21	1.23*	1.26	1.28	1.30	1.35
2C	21	1.02	1.08	1.11	1.10	1.15	1.17	1.19	1.22	1.27
2	24	1.12	1.17	1.20	1.22	1.24*	1.26	1.28	1.31	1.37

For example, the normalised V_{50} for cracked plates is 1.1 of the specified velocity range with 95% confidence that the true V_{50} lies between 1.06 and 1.14. The graphs of the fitted model in figure 7.5 show that older and cracked plates have lower estimated V_{50}'s than later batches, while the confidence intervals in table 7.2 show the degree of uncertainty attached these estimates. For example, the un-cracked plates from batch 2* have a slightly higher estimated V_{50} than those from batch 1*, (*highlighted in table) but the overlap of their confidence limits shows that this apparent difference is probably due to chance. However, both have higher true V_{50}'s than plates from batch 6 cracked or un-cracked.

Confidence intervals are narrower for batch/crack combinations with larger data sets as its effect can be estimated more precisely. The confidence intervals for the V_{05} and V_{95} are wider than those for the V_{50}'s. The reason for this is that the data were collected according to the UK/SC/5449[3] method for estimating V_{50}'s, which mean that in order to establish a V_{50} the majority of the shots were at velocities close to the V_{50}. Because of the large data set at velocities close to the V_{50}, the estimates and confidence intervals for the V_{50}'s are accurate as these are based on interpolation. However, the low number of data collected for some of the tests on cracked plates, e.g. 6C which had only 6 data points grouped around the V_{50}, (highlighted in column n in table 3) meant that in these cases the V_{05} and V_{95} predictions were extrapolations beyond the range of velocities used in the trial.

Part 2. Evaluation of the reliability of soft body armour

This second part of the work would study the reliability of soft body armour panels to perform to their original specification by assessing the degree of variability in the V_{50} ballistic performance of soft body amour that had been in storage for some time. Batches of soft body armour fillers with four different codes and manufacturing dates from 1997 to 2003 were used for the trial. This work would also compare the V_{50} ballistic performance of pre-damaged armour to determine if any of these damaged units dropped below the required specification.

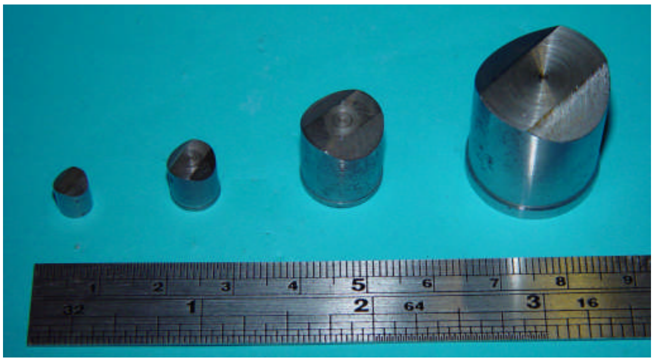

Figure 7.6 Fragment simulating projectiles showing 1.1 gm projectile on far left.

To determine the effects of damage to a waterproof cover and therefore the potential ingress of water into the aramid filler, the V_{50} ballistic performance of dry, wet and wet then dried armour was measured and compared. All armours were constructed from 12 layers of plain weave aramid and 4 layers of ballistic resistant nylon, and were tested following the ballistic test method described in UK/SC/5449[6] with 1.1gram Fragment Simulating Projectile (FSP)
Figure 7.6. Although the spread of velocities allowed for in a six shot V_{50} is $40ms^{-1}$ and is determined by the range of velocities from the lowest recorded velocity for a perforation to the highest velocity recorded for a stop. If the reverse of this occurs, i.e.

when the velocity for the highest stop is recorded at a higher velocity than the velocity for the lowest perforation, it is known as cross-over, and the range (spread) of velocities allowed for a six shot V_{50} can be extended to $70ms^{-1}$. Due to the complexity of the weaves and panel structures this phenomenon is often seen on multi layer textiles. It is often necessary to fire more than six shots at a fabric armour panel to obtain six valid shots i.e. three stops and three perforations, within the $40ms^{-1}$ or $70ms^{-1}$ ranges described above. In this work 156 shots were fired on 35 sets of armour so that tests could be grouped as three six shot V_{50}'s. The maximum number of shots per panel was limited to 18, so that a 50mm space between shots could be maintained as recommended by other standards and researchers [4,5,6].

Figure 7.7 Test set-up for armour tests (left), (right) fragment position of a typical stop

All the tests in the trial were performed on unsupported armour panels clamped at the top edge only onto a target frame, as illustrated in Figure 7.7 with a paper witness sheet to verify perforations. In order that the panel of armour maintained an angle of incidence of 90^0 in plane with each shot, two clamping bars were attached to the bottom of the armour panel with two 'G' clamps. This clamping arrangement weighed 2.3 kg and was not attached to the target frame so that the edge of the armour remained 'free'. Three V_{50} tests were carried out on armour removed from its outer cover (carrier) and in its waterproof cover in the as received 'dry' condition and the results are shown Table 7.3.

Table 7.3 V_{50} trial on batches of dry Armour

Year of Manufacture and armour code	Condition of armour	Velocities recorded as %ms^{-1} over specification			
		Mean V_{50} %ms^{-1}	$V_{50\,\%}ms^{-1}$ Based on six shots	V_{50} Velocity Spread ms^{-1}	Lowest velocity recorded for a perforation %(ms^{-1})
1997 Armour 1	Dry & enclosed in waterproof cover	9.77	13.11 8.88 9.77	26 48 35	8.88 2.88 11.11
2000 Armour 2	Dry & enclosed in waterproof cover	10.88	10.22 11.55 11.77	39 27 40	8.0 7.7 11.33
2001 Armour 3	Dry & enclosed in waterproof cover	10.88	12.66 8.66 11.11	41 39 40	11.77 10.44 6.22
2003 Armour 4	Dry & enclosed in waterproof cover	9.55	5.11 12.44 11.11	18 43 52	4.66 11.33 7.3
Mean V_{50} ms^{-1} for all batches % Over specification		**9.8%**			

The lowest velocity recorded for a perforation in this trial was 2.88% above the specified V_{50} velocity. This velocity was recorded for the oldest batch of armour. The mean values from the three tests on each batch was used to calculate an overall mean which showed that the mean V_{50} of all of the year batches exceeded that of the specification by 9.8% of the expected performance overall. All of the year batches performed well against the specification in this trial and showed no signs of significant deterioration in ballistic properties due to age.

7.4 Wet and wet/dried tests on batch 1

The oldest batch supplied was batch 1 manufactured in 1997. Based on the assumption that if ageing of the aramid was a problem the oldest batch would show the most effects, this batch was selected for the ballistic trials in the wet and wet/dried condition. To simulate ‘worst case’ and allow the aramid to be in maximum contact with the water the waterproof covers were completely removed from the armour panels.

Before the wet/dried ballistic tests were carried out, five sets of armour were weighed then immersed in a tank of de-ionised water for 7 days, removed and hung in sunlight to dry for one day (exposed to UV). The remaining 7 days of the drying period was completed out of sunlight inside the laboratory under natural room temperature drying conditions, until they returned to their original dry weight. Armour (9*) had been soaking in water for two months and three further sets of armour were immersed for a week and tested in the wet condition. The immersed armours were weighed after soaking and the armour absorbed approximately 1kg to 1.5kg of water, irrespective of the time of immersion.

The wet armours were allowed to drain for ten minutes before the test which also included the time to clamp the test specimen to the target and each ballistic test was completed in less than 60 minutes. All the tests in the wet/dry trials were performed using the ballistic test method described above on unsupported armour without the waterproof cover, clamped at the top edge only onto a target frame, as illustrated in Figure 7.7. Sufficient shots were fired to obtain three V_{50}’s on the wet and wet/dried armour and one V_{50} on armour that had been soaked for two months.

Table 7.4 Comparison of wet and dry weights of amour batch 1, in wet/dry trial

Wet/dried trial			**Wet trial**		
Armour code	**Original weight (kg)**	**Dried weight after soak (kg)**	**Armour code**	**Original weight (kg)**	**Wet test weight (kg)**
1	1.45	1.48	6	1.47	2.58
2	1.34	1.39	7	1.40	2.72
3	1.65	1.65	8	1.63	3.27
4	1.63	1.64	9*	1.71	2.63
5	1.47	1.48	* ARMOUR soaked for 2months		

The comparison of V^{50} results from the trial is shown in Table7.5. The soak cycle had reduced the mean V_{50} ballistic performance of the armour in the wet condition by 33%. The armour that had been soaked for two months had similar V_{50} values. This drop in performance was expected as it is known that this type of aramid fibre is not water repellent. However, it was still $15ms^{-1}$ (3%) above that specified in UK/SC/5449[4]

Table7.5 Comparison of wet/dry conditions on oldest armour batch

	Velocities Normalised as % over/under V_{50} specification			
Condition of armour	**Normalised Mean V_{50}**	**Normalised V_{50} Based on six shots**	**V_{50} Velocity Spread ms^{-1}**	**Normalised Lowest velocity recorded for a perforation**
Wet /dried	+1.11	+19 +4.22 +1.11	70 72 31	+0.8 +2.6 +3.7
Wet soak (7 days)	-33	-39.55 -31.33 -28.66	74 36 40	-48.22 -32.66 -30.44
Wet soak (60 days)	-29.55	-30.66	22	-30.88

7.5 Statistical Model

The statistical model developed by Ringrose [7] and described above in order to predict both V_{50}, V_{05} (where 95% of the projectiles are stopped) and V_{95} (where 5% of the projectiles are stopped) velocities and their respective confidence limits was used to analyse the data. This model provides a more accurate estimate of V_{50} and other ballistic limit velocities than UK/SC/5449[4]: all the data can be used rather than just 6 shots and it is possible to provide a more statistically significant result by using the curve shape from different conditions to strengthen the fit of individual curves. The batch to batch variation was observed to be very small and not statistically significant so the data was combined into a single set for each of the three test conditions. The confidence limit gives an indication of how much uncertainty there is in our estimate of the true mean and how confident we are that our mean will be found within these two limits. The smaller the interval the more accurate our estimate will be. The V_{50} results on the dry panels show this, in that the interval is narrow at 20ms^{-1}, Table 7.6. The majority of the shots in this trial were fired at velocities close to the required V_{50} to obtain either a stop or a perforation, therefore it would be expected that the confidence interval for the V_{50} would be narrow so there is a high level of confidence that our mean V_{50} is correct.

Table 7.6 Confidence limits for the values of calculated V_{05}, V_{50} and V_{95} ms^{-1}

Batch		Velocities recorded as ms^{-1} over/under specification								
		V_{05} and 95% Confidence limits			V_{50} and 95% Confidence limits			V_{95} and 95% Confidence limits		
	number of tests	Lower limit	V_{05}	Upper Limit	Lower limit	V_{50}	Upper Limit	Lower limit	V_{95}	Upper Limit
Dry	156	-76	-43	24	26	37	46	91	107	134
Wet/ dried	81	-99	-64	41	-3	16	36	63	86	122
Wet	9	-238	-206	-185	-155	-136	-116	-60	-56	-18

The concentration of shots fired at around V_{50} velocity meant that the confidence intervals for V_{05} and V_{95} were based on extrapolating the limited amount of data to these limits. Therefore the interval between the upper and lower limits is much wider so there is less confidence in the mean value. The UK/SC/5449[4]specification recommends that 50 shots are fired to confirm with almost 100% confidence that a velocity is equal to or less than V_{10} (the velocity at which 10% of the shots could be expected to perforate). The theory behind this can be found in Technical report SCRDE/92/11 July 1992[12]

As there were a low number shots fired at these velocities the extrapolated V_{05} ballistic limit has limited relevance to the specification which is for a V_{50} only. However the extrapolated V_{05} and V_{95} are useful as indicators that some variability in performance would be seen if enough tests were conducted at those velocities. For the soaked and dried panels the V_{50} is still above the specification but only by a small amount so the effect on the 95% confidence limit is to place it below the specification. In the wet condition the panels fall significantly below specification with even the upper confidence limit on the V_{95} being below the specified proof test velocity .

7.6 Summary

This study provides evidence that the V_{50} ballistic performance of complete panels of non-waterproof (untreated) aramid soft textile armour degrades when wet. When the armour is dried, the performance V_{50} recovers to almost that of its original dry condition. The conditions for the wet/dried test were particularly harsh as the covers were completely removed and after soaking the panels were hung in the sun to dry. So they were exposed to some UV degradation whilst drying. This could simulate a real situation of drying out an armour panel, but was not intended to replicate a full environmental ageing test which is outside the scope of this work. Current requirements are that armour should regularly be examined for tears and holes in the waterproof covers. This visual inspection regime appears adequate and there is no evidence to suggest that any damage undetected by this method, such as a pinhole would allow sufficient amounts of water from e.g. an increase in humidity to affect ballistic performance.

There was no significant deterioration in ballistic properties between dry batches that could be attributed to age. All batches in this trial performed well against the UK/SC/5449[4] specification and their V_{50} performance was approximately 10% above the requirement. In this trial the condition of the wet armour was an extreme example as the armour panels had absorbed between 1kg-1.5kg of water. In normal wear conditions it is unlikely that this amount of water absorption would occur through a small perforation or tear in the waterproof cover without a noticeable difference in weight and appearance of the armour. It is also likely that any small ingress of water would evaporate with body heat over time and there would be a recovery of almost all the ballistic performance. Due to the time constraints of this trial, it was not possible to investigate or evaluate the degradation mechanisms in more depth.

The statistical model predicted that under normal conditions a dry panel will always meet the specification and is unlikely ever to be perforated by a 1.1gm fragment at the specified test velocity. Armour which has been soaked and dried out will usually meet the specification but may fail occasional shot, whilst waterlogged armour will in practice never stop a projectile at the specification velocity.

The statistical analysis also predicted that irrespective of plate condition (‘as new’ or cracked) for most batches the (V_{05}) is above the specified velocity limit. For the pre-cracked batches 6 and 5, the 95% confidence limit for the predicted figure does fall below the limit but it is likely that the accuracy of this confidence interval is affected by the low number of shots fired.

Older batches of plates (3 to 6) had a slightly lower performance than more recent batches (1&2). However, it was also found that more than one type of ceramic had been used within these batches, therefore some variability between manufacturers and type of ceramic may account for the slight difference in performance. The ‘‘as new’’ condition plates found to have slight or hairline cracks when X-rayed before testing met the specification, but had a 4-10% reduction in V_{50} when compared to ‘‘as new’’ condition plates without any imperfections. The reduction in mean V_{50} performance pre-cracked plates when compared with ‘‘as new’’ varied from 3.9% for the oldest (batch No 6) to 7.7% for one of the most recent (batch No 2). However, irrespective of crack type, the ballistic performance of cracked plates remained at least 10% above the specification V_{50} velocity. X-ray examination has shown that it will accurately detect the presence of cracks so therefore verify the true condition of the plates.
This part of the study has shown that it is possible to determine the reliability of both hard and soft armour with reasonable accuracy. Therefore, for the armours examined reliability should not be an issue providing the current inspection regimes recommended are followed.

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Chapter 8. General Discussion

8.1 Introduction

The aim of this study was to investigate and optimise some of the effects of wearing body armour. After twenty years of working in this research field the author had identified some areas in the field that merited further investigation and those studied reflect the personal choices of the author. This has introduced diversity into this study and the previous chapters have introduced and investigated several different subject areas that are relevant to improving body amour namely:

The influence of history on modern body armour design
Measurement techniques for behind helmet trauma to the head
Ergonomic effects
Reliability
Flexibility

Until recently these areas of body armour study have been somewhat on the periphery of the subject field whose primary aim has been directed at achieving the correct level of armour protection against a variety of threats. This study has introduced measurement techniques in an attempt to quantify some of the effects investigated with the intention of using these measurement methods to improve armour design and optimise some of the negative ergonomic effects of wearing armour.

8.2 Historical

The influence of technologies developed throughout history upon modern armour systems is undeniable. The ingenuity and complexity of early armours designed to allow the least amount of restriction to the body whilst offering the maximum amount of protection give direction to the development of ergonomically sound modern armours. History shows us that ergonomics is not a new science [1] and is primarily based on intuition and common sense. When early man began to make tools they were an aid to the completion of tasks. As they were generally for personal use, and made for the individual, they were appropriate to the individuals' size and would be adapted until they felt comfortable. The historical review in Chapter 3 has shown us that throughout history when armour was made, the concept of optimizing the protection to consider the ergonomic effects was considered. Much can be learned from the fact that the ancients in their hand to hand combat understood that a well fitting armour was an important ergonomic factor. Their plate armours were cleverly articulated so that as the person moved the armour did not restrict their movements. Armour was tailored to the correct size for the person and museums throughout the world are full of plate armours made for individual kings and their retainers.

Since the re-introduction of the wearing of body armour in the 20th Century modern body armour technology has concentrated on protecting against the threats. It is only recently that work on ergonomics and optimizing armour systems has been considered. Modern military armours are made in a range of sizes but when they are issued they are only an approximation of the size of the individual and there is still much to improve in fitting armour. Police armours are made to fit the individual and body measurements are taken and supplied to the manufacturer with special sizes tailored to the individuals' measurements.

Knife armour was introduced for police armour in the 1990's [2]. The introduction of a standard for knife protection for the Police in 1993[3] has lead to many modern knife resistant body armours being submitted for testing against this standard. As manager of the HOSDB UK body armour test house the author was in the unique position of having access to the many of the knife resistant designs that were submitted for certification. It was noticeable that the first solutions to be submitted were all influenced by ancient metallic systems such as small metal plates or tiles on a fabric backing, plates stitched into pockets of fabric, large plates articulated to fit around the torso and chain mail.

Chain mail was the most successful and has been re-introduced into knife resistant armours in the past 20 years mainly due to its flexibility. The mechanisms of stopping a knife or sharp weapon has not changed since chain mail was first introduced. As described by Horsfall[4] and investigated by Atkins[5] it works by trapping the point of the blade in one of the rings and slowing down the knife as it cuts through the metal ring. To be efficient it requires a backing material to absorb the energy of the impact as the knife is stopped, in modern armours this is often the ballistic component of the armour so the armour protects against both knife and ballistic attack. Each of the small rings of the chain mail can move easily and gives chain mail the ability to drape and flex. This means it adjusts easily to the contours of the human form and is only restricted by the the least flexibleness of the backing armour panel. Because it is composed of links and gaps chain mail is also lightweight, 7mm diameter rings made from 0.7mm diameter steel wire has an areal density of about 2kg/m^2 (Atkins) [5]

To defeat ballistic threats high strength aramid or ultra high molecular weight polyethylene (UHMWP) fibres have successfully replaced natural fibres such as linen, cotton and silk and the early nylon derivatives. Most fabrics have a simple woven structure but recently there has been much work on utilizing new weaving techniques to improve performance. This demonstrates the influence of the complex weaves seen in past armours such as the Samurai or Gilbert Islands armours.

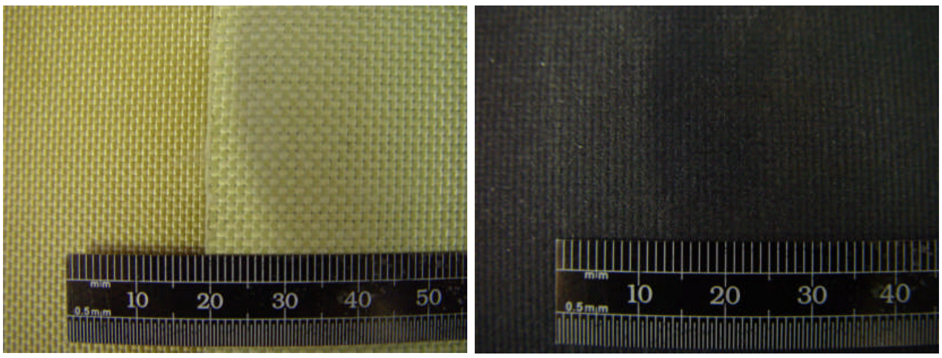

Figure 8.1 Polymer infiltrated aramids (left) grit coated aramid (right)

Knife resistant coated aramids have been developed with technology similar to that of the Chinese Qin dynasty as described in Chapter 3 above. Whereas the Chinese used natural resins to make their ox-hide armours cut proof, polymer resins are used today. In modern armour materials polymers are either infiltrated or coated onto each layer of aramid Figure 8.1 which makes each layer extremely inflexible. Unfortunately when a pack of 20 or more layers is assembled it becomes almost as rigid as an armour plate. The advantage is that these coated systems offer both ballistic and knife protection.

With the McBas body armour system in Chapter 3, figure 3.5 illustrates that there is a requirement for protection for more parts of the body. The technology from the past has still much to offer: for instance, the complexity of the arrangement of plates in ancient plate armours of the past and those of the army depicted by the terracotta army and described by Lin[6] may offer insights into how fabric could be folded to replicate the articulation at the joints. There is much work to be done to improve armours and as discussed above some problems may have already been solved by previous civilizations. The historical development of body armour is still relevant to modern armour today.

8.2 Helmets

Ballistic helmets were introduced to protect the head against fragments and low level ballistic threats as without protection such impacts would result in an AIS 5 (critical) or AIS 6 (not survivable) score. However little is known about the effect of the back face helmet deformation during impact so the purpose of this part of work was to develop a simple robust head form that could be used in a standard laboratory test for measuring forces behind helmets in ballistic/blast trials on helmets. The standard helmet impact tests reviewed in Chapter 2, do not measure behind armour effects only deceleration from a known drop height. Ballistic tests are carried out on the shells of helmets only and the requirement is to stop the fragment or bullet. Blast trials are time consuming and extremely expensive. A laboratory scale ballistic test for helmets that could be extrapolated to blast loading rates would be useful as a development tool. This is a view supported by Anctil [7] who found some correlations between blast and impact tests in his work with an instrumented headform on liner absorbing materials. There is a requirement to reduce the weight of helmets to reduce the overall weight burden on the wearer. Lighter weight helmets may offer the correct protection level, however the deformations caused in absorbing the impact energy may apply fracture loads to the skull. Understanding the magnitude of the impact forces transmitted behind the helmet should help designers improve both the protection levels and ergonomics of helmets.

8.2.1 Influence of calibrations

The results from this initial work show that the head form could withstand ballistic impacts and force versus velocity data were collected. However in the validation of the measurements and the importance of correct calibration cannot be over emphasised for this type of investigation. Unless the forces measured are correct, only assumptions not facts are collected. There are two main problems to be overcome, firstly calibrating the measurements systems and secondly conditioning the electronic measurements signals (filtering) to provide valid data. In this study the transducer output could be easily calibrated before use, by comparing the output of the head form transducer with a similar transducer, calibrated by the method developed at the National Physical Laboratory by Money *et al* [8]. It entails loading the transducer with a known mass, then dynamically unloading the mass and adjusting the output of the transducer to match the force applied by the known mass.

The Zephyr® film gauges proved they could be calibrated against a dynamic drop but unfortunately they were not robust enough to survive ballistic impact loading directly behind the helmets. This is in agreement with similar work by Anctil[9] who had compared the outputs of two polyvinylidine fluoride (PVTF) film gauges with a minature Kistler® load cell after impacts at 20-30 metres per second (the residual velocity that Anctil had estimated from the amount of back face deformation on helmets after 9mm impacts at velocities of approximately 400ms^{-}1). Anctil reported variations in results from both types of (PVTF) sensor and is in agreement with this work. Anctil concluded that Kistler® load cells gave the best results but recommended they should be calibrated. However, Anctil has not suggested a suitable method for dynamic calibration. Although the Zephyr® sensors may not survive a direct load, if they are not placed in direct line of fire and if they can be calibrated, they may be useful for sensing how the loads dissipate over the headform adjacent to the impact area.

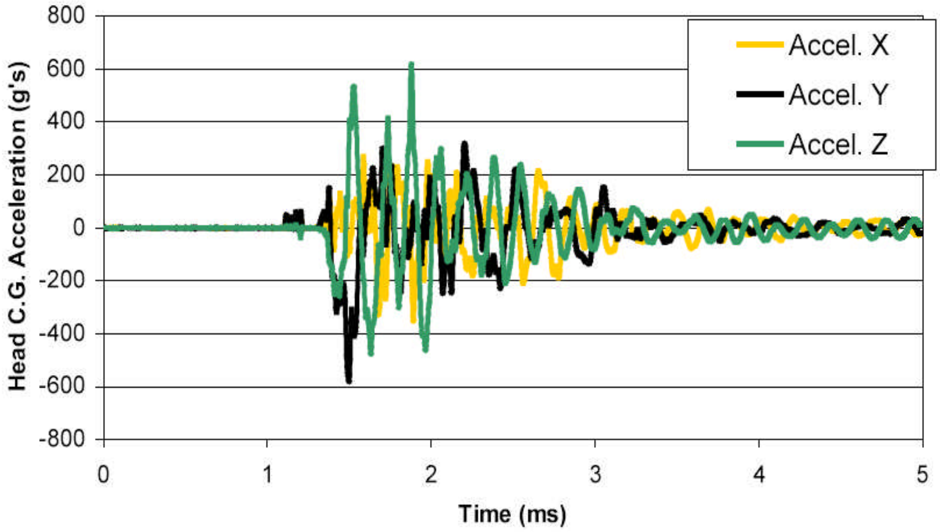

Figure 8.2 Acceleration outputs from Hybrid III crash test dummy (after Bass *et al*) X,Y and Z axes filtered at 40kHz

Bass *et al*[10] had measured head accelerations with a hybrid III crash test dummy and typical result from his work in shown in Figure 8.2. As can be seen, the complexity of these signals makes it extremely difficult to resolve meaningful data such as peak force. If the source can be isolated, such as the natural frequency of the head form, unwanted frequency components can be removed so that meaningful results can be obtained, this is known as 'filtering'. Filtering may help resolve the signal but may not be a true reflection of what has happened in the test. Various methods are used to filter frequency signals. The complete unfiltered time history of head impact and neck accelerations of a 9mm shot as they gradually decrease over 5ms from this study is shown in Figure 8.3. The unfiltered acceleration/time history (light blue) correlates with previous work by Bass *et al* [10] shown above, from 9mm impacts in this study onto helmets mounted onto a modified hybrid III head form.

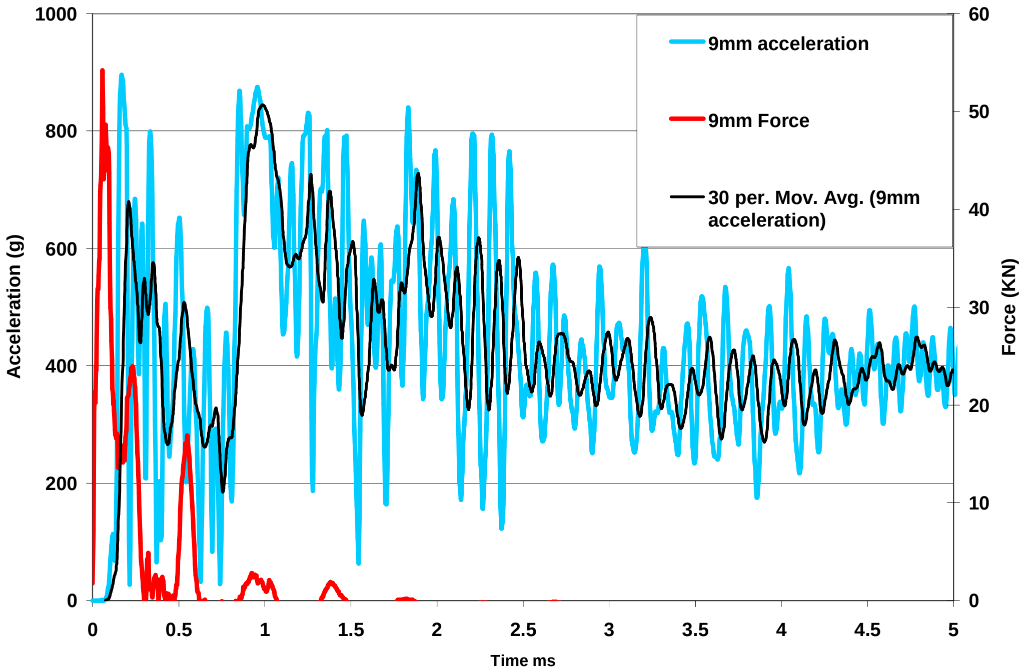

Figure 8.3 Force vs time and acceleration vs time histories of the head impact and neck accelerations from a 9mm impact

The unfiltered force signal is illustrated in red and a 30 point moving average filter was applied to the accelerometer data to resolve the major peaks in the signal for comparison with the force signal. However, the first peak is then reduced dramatically by the filtering. Applying a low-pass digital filter will merely cut out all frequencies above the frequency chosen for filtering and Fourier transform methods may also remove frequency components that are 'real'. To help in interpreting the data the helmets standards reviewed in Chapter 2 apply a 1.6 kHz filter upon the data they collect. This may be appropriate in a drop test lasting for 15 to 30 milliseconds as the peak value may arrive later and as can be seen in Figure 8.3, later in the time history as the frequency signal decays the filtered signal more nearly matches that of the unfiltered signal. For ballistic situations as Figure 8.4 shows the total time component is short at 0.3 milliseconds (as the red trace shows) the time to peak force is 0.12ms and without a filter the force value is 10.38 kN. Applying a 1.65 kHz filter reduced the peak force to 2.72 kN i.e. by 74% and a 40 kHz filter to 9.25 kN i.e.11%. This would mean that the peak force derived by this method may not adequately represent the fast impact event.

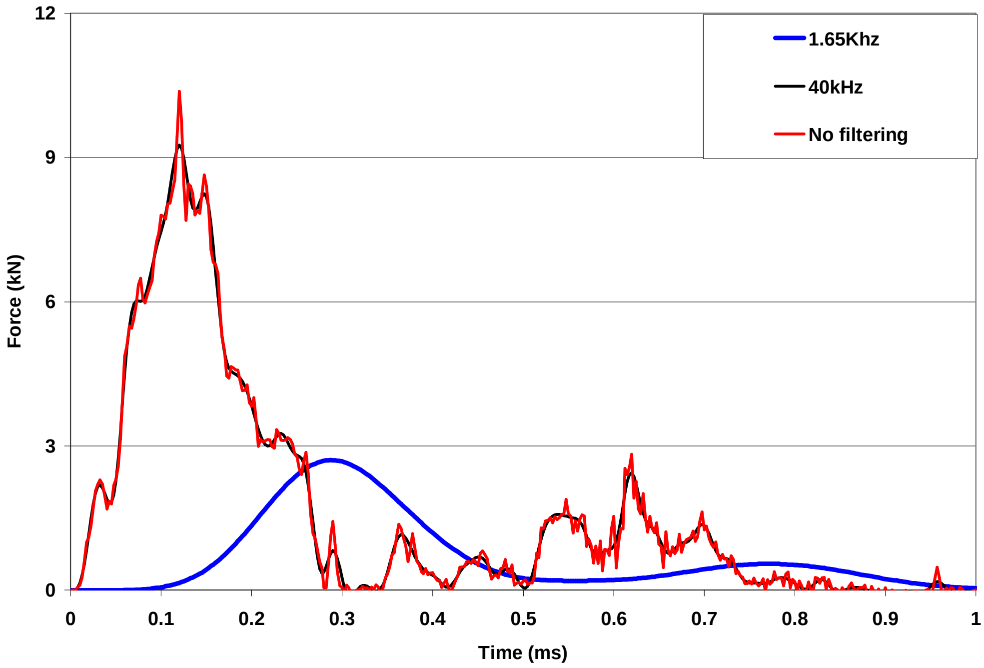

Figure 8.4 Force time history from the same ballistic impact with different filters applied.

The 1.65 kHz filter applied to the data from the force transducer in this work (the blue curve) does produce a 'smooth curve' but it makes the data meaningless as it has reduced the signal significantly. It is likely that many true effects of the impact have been masked by this heavy filtering. The 0.01ms to peak force measured from the head form is 150 hundred times faster than the 15.0ms duration rate accepted as suitable for the calculation of likely head injury by HIC. This is in agreement with Bass[10] who also found that current HIC is not the best method to predict likely levels of head injury in ballistic events and has adopted using a 40kHz filter. Applying a 40kHz filter to the data in Figure 8.4, reduces the peak force but maintains the integrity of the data. However, comparing the 40kHz filtered, with the unfiltered data, shows that in this work the unfiltered Force/time data from the head form transducer produces a sufficiently clear signal so that the 40kHz filter is really unnecessary. Comparing the force data from the head form with unfiltered accelerometer data in figure 8.3 show that the Kistler(R) transducer is producing much clearer data for analysing tests.

8.2.2 Head form tests

There is a degree of confidence in the derived acceleration value of 100g in this study (with an average head weight of 5kg). The extrapolated force values of 4 to 5kN, estimated from the tests on helmets and helmet shells and shown in Chapter 4, Figure 4.2 agree with a Wilber[11]. They are also in agreement with the average skull fracture load of 4.75kN for the parietal area of the skull reported by Allsop[12] and the range of 1.76-4.9kn by Galloway[13]. The figure of 100g also relates to the figures in the blast work by Hill [14] who considered that a blast acceleration of 292g to be well within the range of serious closed head injury. The suggestion that the skull could be fractured by accelerations of approximately 100g is a concern when the current accepted survivability limit is 400g.

The force readings from the ballistic tests in Figure 4.14 in this trial are high at up to 60kN for 9mm ammunition (although was from a test that had almost penetrated the helmet) and 40 kN for 50cal fragments. This is most likely due to the lack of 'standoff' distance allowed behind the helmets and the transducer and that the force results were also unfiltered. The lack of standoff meant that during the 60kN impact event the helmet was in contact with the transducer from the moment the 9mm bullet struck the helmet and continued to be loaded until the helmet materials had absorbed all the impact energy. The peak load occurs in a very short time 0.05 milliseconds and although high may be a true figure. The peak force values of 14kN and 17kN in Figure 4.17 are of the same order and in approximate agreement with Anctil[7] who had also used 9mm ammunition to evaluate helmets without liners. Without a liner, Anctil had measured forces behind his helmets of 10-11kN but all force signals had been filtered with a low pass digital filter that cut off any frequencies above 40kHz. As discussed above, this type of filtering reduces the force peaks in this work by 11%.

The initial results from the instrumented head form developed in this study are promising and the force signal measurements from the transducer are much less noisy than accelerometer signals. Further work on acceptable levels of filtering for the force signals will need to be done so that comparable work can be completed.

Understanding the threat levels to the head and being able to make accurate measurements should aid the development of the correct amount of protection that needs to be provided for the head. Then it may be possible to introduce lighter weight helmets to reduce the ergonomic effects of head protection.

8.3 Ergonomics

This study has shown that useful data can be collected from short ergonomic trials. There is much published data about Ergonomics and Human Factors relating to the workplace however as the literature review in Chapter 2 showed there is less published information relating to the ergonomics of wearing body armour. The movements in the current standard CEN ISO procedures reviewed in Chapter 2 do not seem to be accepted as being relevant either by the author or Zamir [15] and Iremonger & Couldrick [16].

8.3.1 Armour sizing

As body armour is a clothing garment worn close to the body, assessing its ergonomic effect will always be very subjective and personal. Although Police Officers are measured for a personal fit, their measurements are matched to the 'best fit' from a range of sizes supplied by the manufacturer. The measurements taken are around the chest and waist and a neck to waist measurement for body length. Minor adjustments are usually accommodated by an adjustable belt at the waist. A person with an overall chest measurement that matches a particular size will be issued with that specific size. However, problems occur when an individual has a chest measurement that comprises of less or greater than half of the chest circumference i.e. a smaller measurement across the back combined with a larger measurement across the front of the chest. This situation occurs more often in females and combined with the fact that the front female form also curves into the waist does cause additional problems.

8.3.2 Effect of armour on wearers

The inability of body armour to flex and drape is due to the performance requirement. Aramid body armour panels require many layers of fabric to stop a bullet,
Figure 8.5. This can make the ballistic pack very thick and inflexible. It is the inflexibilityness of the multiple layers of aramid fabrics when they are sewn into a panel that cause most of the ergonomic problems for the wearer. These panels are usually inserted into a 'carrier' which is part of the uniform for the officer. The fabrics of the carriers are usually washable so of necessity they are made of durable fabrics which also add to the inflexibilityness. The result is an inflexible armour that restricts body movements when bending from the waist especially. Also inflexible armours tend to 'ride up' on the body making actions such as sitting in a vehicle difficult as the front of the armours can compress the throat.


Figure 8.5 Bullet captured in aramid pack (courtesy of Teijin Twaron)(left) Typical armour used in the trial (right).

8.3.3 Study Design

Choosing the movements for this study was extremely important and analysing movements that would most accurately replicate typical movements by Police Officers was the primary aim. As reported in Chapter 5 there was a lack of confidence in previous trials as there had been little control on the exact movements the officers had performed. They had been asked to wear the armours in the course of their duties so the movements would have been 'real' but as they were random and not recorded they were difficult to assess. After consultation with the users and the Personal Protection Group team at the Metropolitan Police, the actions detailed in the ergonomics trials section of Chapter 5 and illustrated in Figures 5.6 to 5.11 were chosen as acceptable to fully assess areas on a body armour that might cause discomfort. Following the standards review in Chapter 2 some of the movements from the ISO/FDIS 14876-1 (2002) such as across and behind body reach were thought to be useful, but the manner in which the questions were posed was not. Most of the questions asked the user to assess more than one property of the armour and differentiating between what was a 'slight problem' and 'problems of comfort or impediment' did not isolate the particular part of the armour where there was a problem. Therefore in the design of the questionnaire for this study the questions chosen were precise so that only one action was scored. The scoring system was also precise and directed the wearer to either a positive or negative choice, there was no chance for the wearer to respond with a 'don't know' answer. Tolerable was included and this was allocated a score of 2. Galer[1] and other ergonomists have long recognised that people are adaptable and can tolerate poorly designed equipment but there are limits to the amount of adaptation a person can reasonably asked to make. When a body armour chafes or pinches or causes bruising this is not acceptable and therefore not tolerable. Following the principle that the 'simplest way to get an answer to any question is to ask the person' Parsons [17], a section for comments was included and this section was invaluable in re-inforcing some of the scores the wearers had made.

The questionnaire was designed to fit on one side of an A4 sheet of paper with simple 'tick boxes' to score each question. The reaction to the questionnaire from the Police Officers in the trial was very positive. They found the questions very straightforward and needed little direction in filling out the forms. They immediately identified with the actions and questions being asked and commented that they were relevant to their normal duties. Previous work by Iremonger *et al*[18] had also used a one page questionnaire for some simple trials with military users but their form had been more open to interpretation and the two choices for ranking and scoring four tasks were ‘easy’ or ‘difficult’. This form had also been more confusing for the subjects to understand.

The design of the forms meant the scores were easy to abstract, before entering into the spreadsheet. The mean values of the scores for each activity shown in Figure 5.14 were a simple first analysis and proved to be illuminating. Each of the six armours were able to be ranked in order of preference and the standard deviations from the mean for five of the armours were low, indicating all wearers were in agreement with the scoring for each of the questions. Armour number three had the lowest scores and more areas of this armour caused irritation to the wearers, this was reflected in the armour having the greatest variation in standard deviation from the mean.

The ability to attribute a numerical score to an action meant the data could be analysed from the spreadsheet quickly. An example of this is shown in Chapter 5 Figure 5.15 where the individual mean score for each action from armours 1, 2 and 3 is plotted. The individual action is described on the x axis and for example when asked to score ‘how easy was the armour to put on?’ and ‘how easy was the amour to adjust to fit? the scores show that armour 3 scored much less than 1 or 2. In this instance this was due to the complex design of the strapping arrangement shown in Figure 5.5. These results were found to be very useful in discussions with the manufacturer on improving the design. Koerhuis[19] and Ashby[20] used reduction in speed to complete tasks whilst wearing body armour and whilst this method is useful in a comparative test to select a particular armour system it does not offer information on particular problem areas that could be improved by the design.

Couldrick and Iremonger [21] developed a human factors integration axiom to show a functional relationship (rather than a mathematical equation) for the balance between performance and protection to aid the comparison of different protection systems. They attempted to assess the limitations on the effectiveness of the individual imposed by wearing body armour against the risk of not wearing body armour.

They proposed that the effectiveness of armour equates to:

Protection level x area of coverage x time worn x 1-(reduction in performance).

Where:

$$\text{Protection level} = \frac{\text{Probability of number of impact stopped}}{\text{Probability of the total number of impacts}}$$

$$\text{Area of coverage} = \frac{\text{Sum of all regions (vulnerability of region x area protected)}}{\text{Sum all regions (vulnerability of region x area of region)}}$$

$$\text{Time worn} = \frac{\text{Sum of all time increments (risk during increment x time during increment with armour)}}{\text{Sum all time increments (risk during increment x duration of increment)}}$$

The reduction in performance is assessed by materials assessments, proof testing and user trials. This may be a useful selection tool, but in their analysis Couldrick and Iremonger [21] were examining the risks of injury to EOD operatives, where the risk of injury is high and the burden of the armour systems is great. So, for this study where the protection level was the same for all armours, the areas of coverage similar, and the level of risk of injury whilst wearing armour small. This axiom was of little value.

The purpose of the trials described above, were to offer some positive ‘feedback’ to the manufacturer specifically to address problem areas that could be improved. The results also highlighted areas that worked well and would not require change. The reasoning was that if problems were identified and corrected at an early stage in the development phase of body armour there would be significant cost savings and a better acceptance of an armour system when it was issued.

8.3.4 Number of subjects

From the literature reviewed in Chapter 2, it was shown that body armour standards vary in their recommendations with regard to the number of subjects necessary for an ergonomic trial from six to ten subjects. Military trials base their work on a troop of soldiers (30-40 subjects) and police a percentage of the expected number of armours purchased. To investigate if valid data could be obtained from reducing the number of subjects from thirty to ten. Three armours (4, 5 and 6) were trialled and compared with the results from the thirty subjects used for trials on armours 1, 2 and 3. In the analysis we are normalising the data by dividing the total scores by the number of subjects, i.e. obtaining a figure for an average individual from a sample of either thirty or ten subjects. Figure 5.14 compares the results from thirty (armours 1,2,3) and ten subjects (armours 4,5,6). It shows that the mean values from ten subjects are still able to differentiate between small differences in the armours. Amours 5 and 6 were the same carrier but had different panels inserted and therefore it was expected that the scoring would be similar. The scoring was close, but armour 6 achieved a slightly higher score indicating the panel in that armour was more uncomfortable. Weimar[22] advises that the sample size should be a balance between being large enough for accurate data to be collected and small enough to be cost and time effective. The data collected from these trials have shown that it is certainly practical to use ten subjects to assess armour which would mean a time and cost effective ergonomic trial. Further work could use this method to trial armours with six subjects to validate the numbers recommended in the current standards.

8.4 Flexibility

Armour flexibility is an important property that improves the ergonomics of the body armour and it would be useful to have a test method to assess this. The test method based on the ASTM D4032-92 circular bend test [23,24] has been shown to be able to discriminate between inflexible and flexible armour test samples. The data from the first test on each sample type from each manufacturer is shown in Figure 8.6. Armours F and L were the least flexible of the armours tested and this is illustrated by the steeper gradient of the curves and the shorter distance to reach the maximum load in these tests. E, H and J were the most flexible of the armour panels. K was slightly less flexible than the most flexible armours in the first test but was a better match after the second and third tests. The ability to measure the displacement of the complete panel for a given load is more realistic than measuring the flexibility of one layer of fabric as flexibility becomes an issue when there are multiple layers of fabric.

Manufacturers and fitters will adjust the armour until it fits the torso tightly. In reality the user adjusts their armour until they perceive it to be a comfortable fit which in practice allows the armour to move freely with the body.

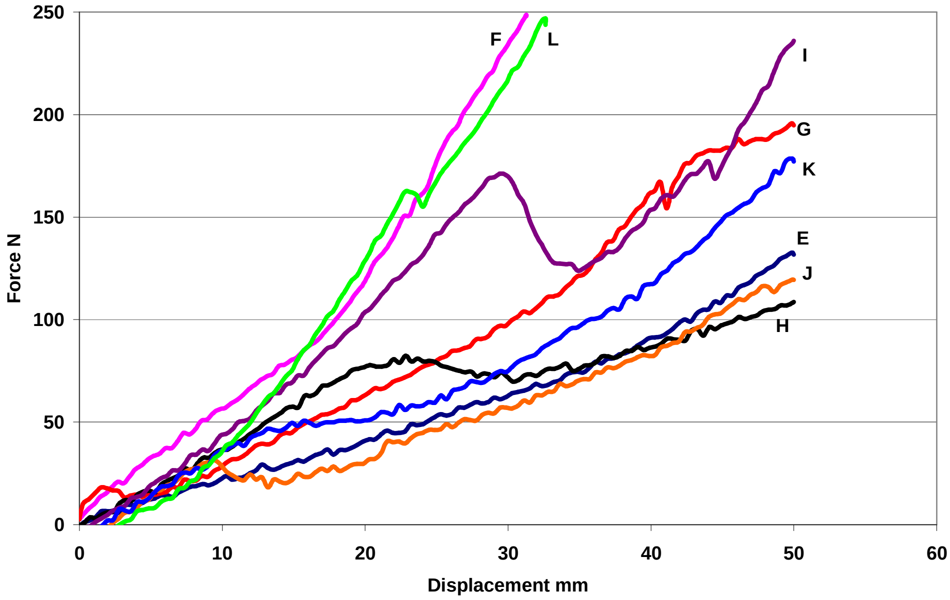

Figure 8.6 Comparison of the mechanical flexibility of eight different armour solutions

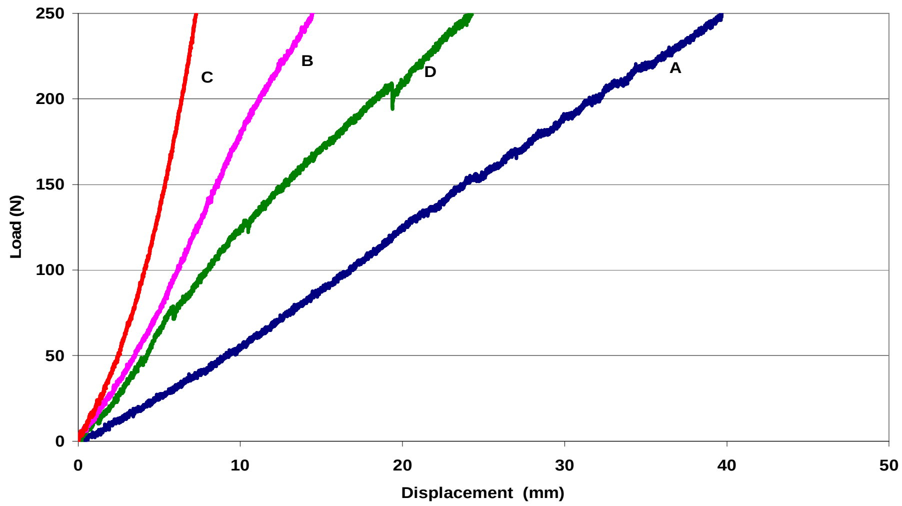

Figure 8.7 Armour ranked by instrumented flexibility test with retaining ring

The argument for restraining the body armour panels during the test is that it makes the test more repeatable. The results from this trial have shown that not restraining the armour during the test gives reasonable results after the first test and also assesses the ability of the armour to form folds.

However if we are looking to have a 'standard' test the retaining ring method will help to eliminate any variance from one test laboratory and another. Figure 8.7 illustrates graphically the effect of using the retaining ring. It can be seen that there is a clearer definition between one armour panel and another and the traces rise more steeply due to the panels being restrained. The steepness of the gradient of each trace could be used to determine a modulus for each panel but for standard comparative tests this may not yield any useful data. The force/displacement measurements are simple and easy to interpret which for standards is always preferable. BSI[25] defines a standard as 'being an agreed repeatable way of doing something' and tests should be as straightforward as possible to avoid variation between test laboratories.

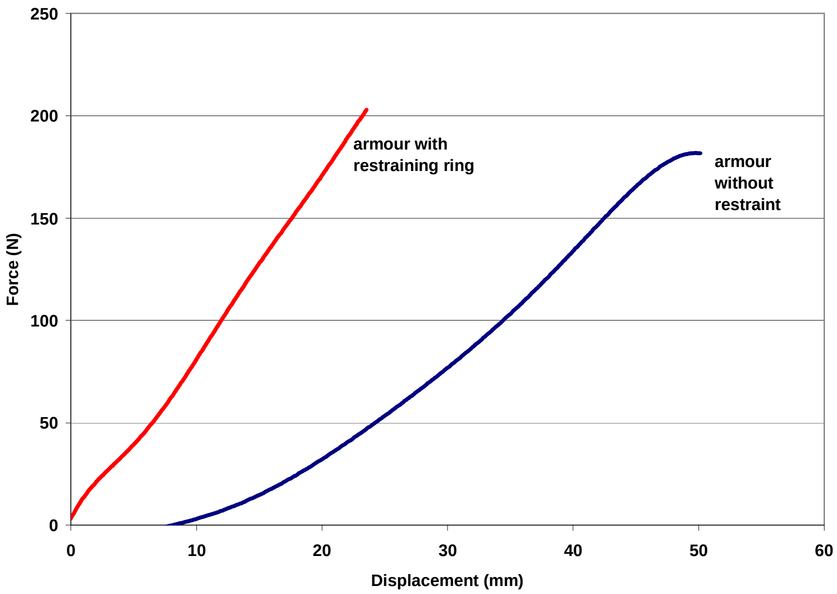

Figure 8.8 Comparison of flexibility with and without restraining ring on one armour type.

The retaining ring reduces slippage and prevents the armour panel folding. The effect of the retaining ring on one flexible armour type is shown in Figure 8.8. As expected the effect of the restraint is to produce a steeper gradient and the armour displacement is less than the test without the restraint. For standards purposes the use of a retaining ring would ensure that variation between test houses was reduced.

Comparing the results from the flexibility trial with those of the same armours worn in the ergonomics wearer trials Table 8.1 shows that the mechanical flexibility trial can differentiate between flexible and non flexible systems. However, it does not relate directly to the perception of the wearer when ranking the armour. As can be seen armours F and L (which were armours number 6 and 3 in the wearer trial) were the least flexible in the flexibility trial as their displacements were less at maximum load. The remaining armours showed some degree of flexibility but it was not possible to match the load to maximum displacement with the scores from the wearer rankings.

Table 8.1 Comparison of ranking from ergonomics wearer trial with mechanical flexibility trial

	Ergonomic trials	**Mechanical Flexibility test**	
Armour	**All subjects Ranking**	**Force N**	**Displacement mm**
2(I)	98.03	134	50
1(G)	93.93	195	50
4 (H)	88.60	109	50
5 (E)	81.50	177	50
6(F)	83.00	250	31
3(L)	61.63	250	33

Misshoun [26] concluded that the circular bend test gave the most accurate results on armour materials but needed improvement as the probe size used was too small. The modified test described above has a larger probe diameter that allows a larger surface area of the panel to be tested so is closer to replicating how armour wraps around a torso rather than a point loading from the probe tests.

8.5 Reliability

8.5.1 Ceramic Body Armour Plates

Ceramic armour plates are sold as being robust but manufacturers also recommend in their care instructions that the user is very careful not to drop them in case the ceramic front face cracks[27]. This somewhat contradicts the fact that ceramic armour plates stop rifle rounds. The concern is that if a bullet impacts directly on a crack the performance of the plate will be compromised. Armour plates are manufactured from high strength ceramic materials such as Alumina which is harder than the material of the rifle bullet. When the rifle bullet impacts on the armour the interaction between the plate and the bullet causes the bullet to be disrupted and the ceramic face under the impact point is pulverised (comminuted) into a powder Hazel[28] which slows down the speed of the impact to allow a softer backing material attached to the plate to absorb the energy of the impact. Any fragments of ceramic and disrupted bullet are caught in the backing material.

Standard ballistic testing for these plates is always carried out on new plates and there is little published data about the effects on ballistic performance of any hairline cracks in the plates that could develop through wear and tear. This study has shown that a Non Destructive Test (NDT) i.e. X-ray examination will accurately detect the presence of cracks and verify the true condition of the plates. This work is a significant improvement on a previous study in 2000 by Bourne *et al* [29] which had used ultra sound scanning. Ultra sound (C-scan) type of measurement is usually carried out under water using the water as a coupling agent, Bourne *et al* had rejected this method as being unsuitable as the images were not clear and immersing the plates could lead to water damage. Also ceramic armour materials are highly attenuating and the frequencies used at that time (1-10MHz) were impractical. An alternative method using air as a couplant had been proposed to scan plates to check for defects. A 120KHz probe was developed and the quality of the images was much improved being able to identify defects but the resolution could not identify areas less than 5mm in diameter.

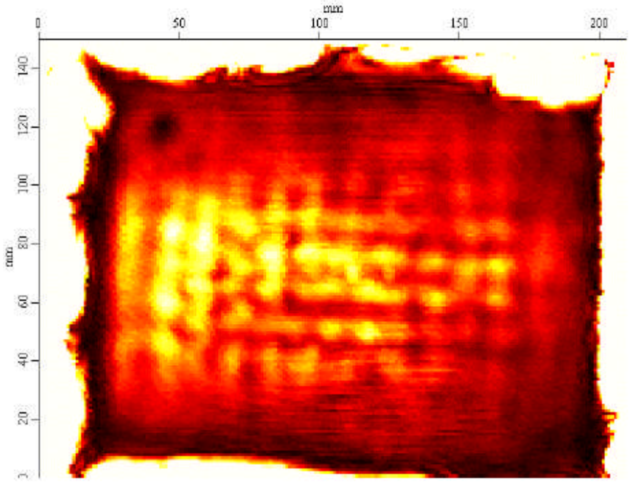

Figure 8.9 Ceramic Plate inspected using the air scan ultra sound test method (after Bourne *et al* [29]

Roberson *et al* [30] used a sonic transmitter and receiver to scan ceramic plates as an alternative to X-rays. Roberson *et al* [31] produced signal outputs similar to those seen on an oscilloscope. This method requires interpretation of the amplitude of the signal and the frequency components, a low frequency indicates cracks are present and the variation in amplitude across the plate how many cracks are in the plate.

Figure 8.10 Digital X-Ray image of cracked ceramic plate (courtesy of Xograph Imaging [32]

Roberson proposed that sonic resonance could be used to indicate the presence of cracks and X-ray to determine their position. As X-rays can determine both the presence and position of the cracks, sonic resonance seems to have been overtaken by the X-ray technique developed in this study. Xograph Imaging has developed Digital X-ray systems[32] that can process high quality images of ceramic plates very quickly and would be suitable for quality control inspections. However, boundary conditions need to be established for rejection, as plates with cracks were shown to meet the requirements of UK/SC/4898[].

Plates with cracks invisible to a visual inspection, but visible when X-rayed before testing, met the specification, but had a 4-10% reduction in V_{50} when compared perfect condition plates without any imperfections. The reduction in mean V_{50} performance of pre-cracked plates when compared with plates in perfect condition varied from 3.9% for the oldest to 7.7% for the most. However, irrespective of crack type, the ballistic performance of cracked plates remained at least 10% above the specification V_{50} velocity. This is in agreement with work by Horsfall and Bishop[33] who after introducing cracks into ceramic panels by three point bending found that the induced cracks caused a drop in V_{50} performance of 3%. Although cracks in plates caused a drop in performance the statistical analysis predicted that for most plates the (V_{05}) continued to be above the specified velocity limit. For the pre-cracked batches the 95% confidence limit for the predicted figure is below the limit but it is likely that the accuracy of this confidence interval may be affected by the low number of shots fired.

8.5.2 Soft Body Armour

The quality control of armour samples is usually completed by manufacturers [34,35] to ensure that they control the quality and consistency of their armour at the production stages. The results of these tests are rarely published and are usually commercial in confidence as any reported failures would be detrimental to the company. A classic example of over confidence in a new product occurred in the early 2000's. It was the incident involving the fabric Zylon® made by Toyobo[36]. In comparison testing Toyobo had reported that tensile tests on the fabric had shown its performance to be twice as strong as ballistic aramid fabric. This was hailed as an advance in technology and a major breakthrough in reducing the weight and thickness of armours. Zylon® was quickly adopted by many manufacturers who either included it in their armour designs to reduce bulk or produced armours completely made from Zylon®. However, when an officer in Pennsylvania in the US[37] was shot and killed in 2003 whilst wearing this type of body armour an investigation was launched by the US Attorney General. The reaction of the body armour manufacturer Armour Holdings Incorporated was commendable in that they offered to replace the faulty armours with aramid armour. The cost of this and the effect of lack of confidence in their company resulted in the company making huge losses[37].

Aramid fabric suppliers such as Dupont[38] will guarantee the performance of the fabric as supplied on a roll for a five year period, however it is less clear what is guaranteed once the roll of fabric has been cut and stitched into an armour. This has lead to some manufacturers of armour issuing five year guarantees on their armours [34,35] without a full assessment of the effect of wear or degradation over that time of an armour that has been worn. As these five year guarantees expire this has resulted in Police Forces deciding to replace armour after five years irrespective of whether the armour performance has been maintained.

The performance quality of body armours internationally is largely mainly assessed by ballistic proof tests and these are still the primary adjudicated tests for the control of quality and consistency. The US National Institute for Justice (NIJ) 0101.06 Body Armour Standard [39] requires that ten armours of the same construction to be proof tested for certification to its standard. Once an armour design has been certificated it carries the certification regardless of how many armours' are sold or for how many years they are worn.

Until 2007 the previous UK Home Office Scientific Development Branch (HOSDB) Standards (1999[40]& 2003[41]) were similar to NIJ in that they only proof tested one armour regardless of how many armours were sold. It was assumed that the individual

Police Forces in their tender processes would set up arrangements with the manufacturers for the quality control of armour when large numbers were purchased and this certainly was the case for the Metropolitan Police[42]. However, smaller Police Forces purchasing small numbers accepted the HOSDB certificate as being sufficient. After the Zylon® incident described above this led to HOSDB modifying their Standard to investigate the reliability of armours to perform consistently after time.

Currently the HOSDB Body Armour Test Standard for UK Police 2007[43] is the only test standard to introduce a method of testing armours after a period of time has lapsed. It has introduced a Manufacturers Quality Test (MQT) into its 2007 Standard. The number of armours tested for certification has been increased to seven and it requires that all soft body armour should re-evaluated after five hundred armours have been sold (MQT1) either at their own factory or a certified test facility. Furthermore after five thousand armours have been sold or two years have elapsed (MQT2) the armour will have to be certified again and the new certificate will be valid for a further two years. For ceramic plate armour the number of units drops to one hundred for MQT1 and five hundred for MQT2. This standard goes some way to addressing the reliability of quality and consistency of the product to meet a performance level as they are produced. However, the MQT tests are still testing new armours, so the standard does not assess the possible degradation of performance over time.

HOSDB also recommends assessing degradation by a ‘dip test’ whereby armours that have been worn are withdrawn at random from the users and re-tested to see if they meet the standard. This should result in some data on degradation on other body armours being available for comparison with this work. As the HOSDB standard was introduced in late 2007, armours that were certified in 2008 are just being re-tested to MQT and at the time of writing it is still too early for the publication of any degradation data.

It had been reported many times in the press that the degradation of Zylon® may have been due to water ingress from perspiration. Holmes [44] investigated the degradation of the Zylon® fabric described above scientifically by testing and comparing the differences in tensile strength of fifty individual Zylon® fibres pulled from a new armour and two worn armours and the evidence armour. There was a reduction of 17-29% in tensile properties in the evidence armour compared with the new armour. However, Holmes also saw variations on other panels and acknowledged the difficulties in extrapolating from the mechanical properties of the microstructure to the complex composite structures of multi layered armour. The investigation by Holmes is still ongoing [39].

The importance of the work in this study is that it has provided new evidence that dry aramid panels show no degradation due to age even when the oldest panels were ten years old. However, when wet the performance of a non-waterproofed aramid panel is degraded. The 33% drop in performance confirmed was similar to those reported by Pushpa[45]and Kruger[46] in that there is up to a 40% reduction in the ballistic protection when a non-water repellent aramid is wetted. It has been suggested by Scott[47] and also by Tobin[48] that this is a mechanical effect that when wet, the inter- fibre friction of the aramid goes down and this adversely effects the interaction of the aramid with the fragment. In effect the water between the fibres is acting as a lubricant to the fragment. It is encouraging to note however, that in this study the performance of the aramid recovers after drying. Drying the panels effectively restore the condition to almost the original condition. It was shown that the difference between dry and wet/dried aramid filler was only 3%. This study should provide a degree of confidence in the continuing reliability of undamaged body armour beyond the current typical guarantee period of five years and until such time as the regular testing regimes such as those instigated by HOSDB have time to mature. HOSDB tests are on whole armour systems only and further work on other types of aramid materials should be undertaken to establish a baseline for each fabric type that could be used as a reference for future ageing comparisons.

This study has taken a broad view and investigated the behind armour effects, ergonomics, reliability and flexibility which are some of the important factors in the field of body armour research that still needed to be addressed. Measurement methods have been introduced with some success in an attempt to quantify some of the parameters that could then be used in further work to optimise the negative effects of wearing body armour.

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Chapter 9. Conclusions

All researchers read previous work in the field before beginning a project. This work has shown that in this field there is much to learn from thousands of years of development and history should not be ignored. The influence of ancient technology upon armour developments has shown innovation in the techniques used by our ancestors to optimize their armour systems. "*Do not re-invent the wheel*" is the first conclusion I have drawn from this work.

Measurement techniques that can be used to determine impact forces behind helmets and methods of dynamically calibrating sensors for ballistic tests on a head form have been developed. This work has shown the importance of understanding the responses from measurement tools before gathering data. Accurate calibration of measurement systems is of particular importance for impact work as the events are high speed and data signals are complex and difficult to resolve.

This work has shown that the filtering techniques used in the current helmet test standards are not applicable to high speed impact events. The current 1.65kHz filter used for crash test simulations reduces the peak impact forces by up to 75%, and therefore may underestimate the peak forces from high speed event. This study has found that unfiltered force traces from force transducers produce clear signals that require no or minimal filtering.

A new method of evaluating the ergonomic effects of wearing body armour has been developed for the National Police Improvement Agency. This method was successfully used to evaluate the new HG1A/KR1 body armour system submitted for the UK Police National tender. It has lead to the early detection of several design problems that have been rectified before the armours have gone into full production and been issued to officers. The author presented the results of this work to the Associated Chief Police Officers (ACPO) body armour group at the National Police Improvement Agency in September 2009. The methodology has subsequently been adopted by the Metropolitan Police for a further ergonomic trial on body armours for Firearms teams. The author is a also a member of the CEN/TC 162/WG 5/PG 5N working group on body armour standards and there is interest from this working group in incorporating the methodology developed in this work into the CEN EN 14876 Body Armour Standard Part 1, General requirements.

The flexibility of armour influences the ergonomic effects and measurements from the mechanical flexibility test give a good quantitative data of the flexibility of an armour panel. The test was able to discriminate between stiff panels and flexible armour panels but a direct link between ergonomic rankings and flexibility could not be established.

The reliability of ceramic plate and soft body armour systems to meet their performance criteria over time has been demonstrated. This data has provided a degree of confidence that older undamaged armour systems will still continue to perform adequately to their original specification. It was encouraging to find that irrespective of crack type, the ballistic performance of cracked plates remained at least 10% above the specification V_{50} velocity. Also that the performance of waterlogged soft body armour is reversible and after drying the performance returns to almost the original specification.

The logistic regression method used to analyse the data has been shown to be of value. It is useful to be able to use the confidence limits and be 95% confident that the reliability of the V_{50} value is within these limits.

X-ray examination has shown that it will accurately detect the presence of cracks so therefore verify the true condition of the plates. With the introduction of digital X-ray it is now possible for the manufacturer to check the condition of plates at any stage in their life cycle.

Chapter 10. Recommendations for Further Work

Ergonomics tests should be part of every body armour procurement process. The work on the ergonomic factors of body armour is continuing and further work needs to be done in refining the analysis techniques. Identifying movements which are critical to undertaking the performance of an officers duties and allocating an extra weighting factor to these may help isolate even more problems.

Effort should be made to ensure that armour maintains its protection levels for the period of service and all the armour meets the standards of the original test items. The reliability of ceramic plate and soft body armour systems to meet their performance criteria over time has been demonstrated for one of each armour type. This work needs to be expanded to incorporate other types of armour systems.

There is still much that could be done in understanding the effects of filtering techniques. The signal outputs from transducers merit more investigation to determine an optimum filtering level for each application. As technology advances new developments in instrumentation for high rate testing have meant that the sampling rates have improved so that measurements of high speed events can be captured accurately and with better resolution. Further work should investigate the methods of measurement especially dynamically calibrating sensors in situ.

For both research and assessment procedures it may be necessary to use more complex procedures, to properly quantify the risk and performance of body armour and other PPE.

Appendix A

AN ASSESSMENT OF THE BALLISTIC PERFORMANCE OF CONTOURED PROTECTIVE BODY ARMOUR PLATES

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An assessment of the ballistic performance of contoured protective body armour plates

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Abstract

This work determined the effects of batch to batch variation, deterioration due to age and induced cracking on the ballistic performance of contoured protective body armour plates. Cracks were introduced into batches of plates, X-rays were then used to determine the positions of cracks and the ballistic performance of these cracked areas evaluated. A statistical analysis of all results was performed in order to assess the V_{50} velocity and the velocity at which the failure probability was less than 5% (V_{05}).

It was found that all batches of plates assessed as A1 condition exceeded the ballistic specification by at least 15% and even when severely cracked the ballistic performance remained at least 10% above specification. No evidence was found of any construction effects, defects or deterioration due to age that resulted in a reduction in ballistic performance.

Introduction

The aim of the research was to determine the degree of variability in the ballistic performance of six production batches of contoured protective body armour plates classified as being in A1 condition. Damage was then induced into a selection of production plates from the same batches and any change in performance against the UK/SC/4898[1] specification was determined and compared with the performance of undamaged plates. The ballistic trial evaluated the performance of the plates against 7.62mm x 51mm ammunition. To compare the performance of the plates accurately, the condition of the plates was verified by X-ray before and after damage was induced. One batch of rejected plates with clearly visible damage was also evaluated.

V_{50} Evaluation of the ballistic performance of ceramic armour plates

The UK/SC/4898[1] specification is a proof test to confirm that the plates stop the designated ammunition at a specified velocity. However, to evaluate the performance of one plate against another, a V_{50} method is normally used where the velocity at which the plates are perforated is determined. A V_{50} is defined as the velocity at which, with the specified projectile and target material the estimated probability of penetration is 0.5 [2]. The UK/SC/5449[3] specification defines the range (spread) of velocities allowed for a six shot V_{50} as $40ms^{-1}$. This spread is bracketed by the lowest recorded velocity for a penetration and the highest velocity recorded for a stop. In this trial three V_{50} ballistic tests were carried out on each of six different batches of plates, representing 12 years of production. All the V_{50} tests in the trial were against plates supported by CBA soft body armour which was strapped onto a conditioned Plastilina® backing with one shot aimed at the centre of each plate tested.

Results of V_{50} trial on A1 condition plates

The results for all six batches of A1 plates tested showed that following the test methodology for calculating V_{50} described in Annex B of the UK/SC/5449[2] specification all of the A1 condition plates exceeded the specified velocity range. Figure 1 shows that the performance of these batches was 16% to 24% above the limit specified.

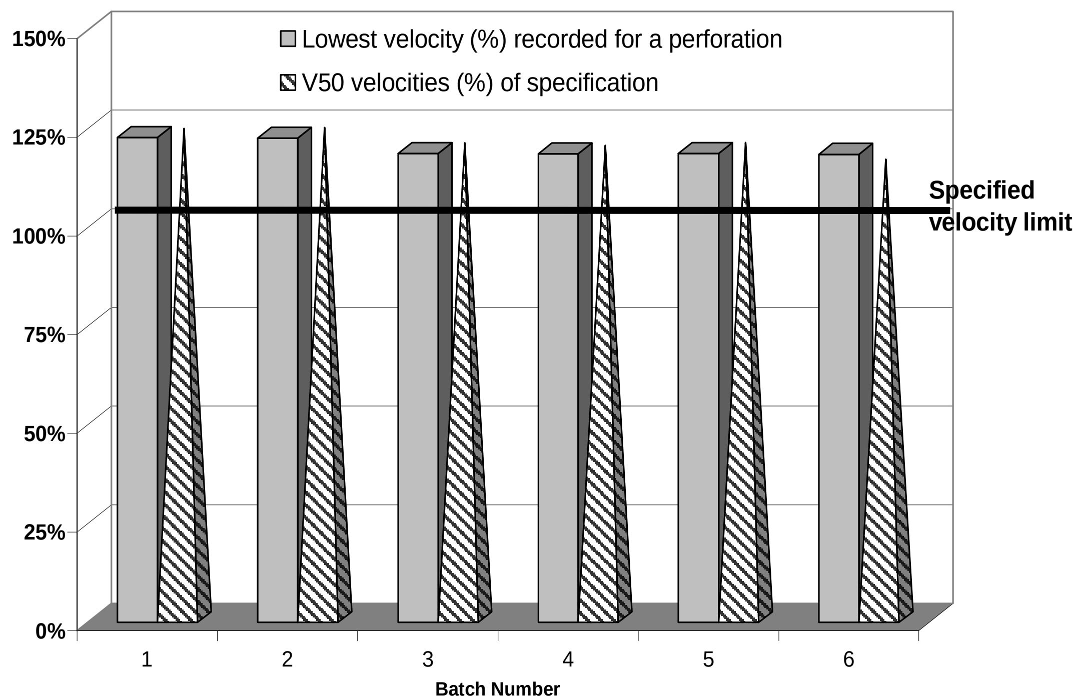

Figure 1. Comparison of V_{50} velocity for all batches of plates in A1 condition against specified proof test velocity limit (%) and lowest velocity recorded for perforation for each batch type (%)

Results of V_{50} trial on pre-cracked condition plates

To study the effect of cracks a number of A1 plates from the most recent production years (batches 1&2) were 'pre-cracked' in a hydraulic press. Sufficient load was applied until the plate cracked a distinct noise indicated this happening. After this they were checked visually and there were no clear signs of damage at the surface. These plates were X-rayed to show the positions of the cracks. The X- rayed plates showed definite severe cracking in all cases, a typical example of an armour plate showing induced pre-cracks and shot position is shown in figure 2. The X-ray's were scaled 1:1 with the plates so the X-rays could be used as a template to transfer the pattern of the cracks and mark up each of the test plates, figure 3. Three V_{50} ballistic trials were performed on these pre-cracked plates with the shot position aimed at the area of the plate with the most cracks.

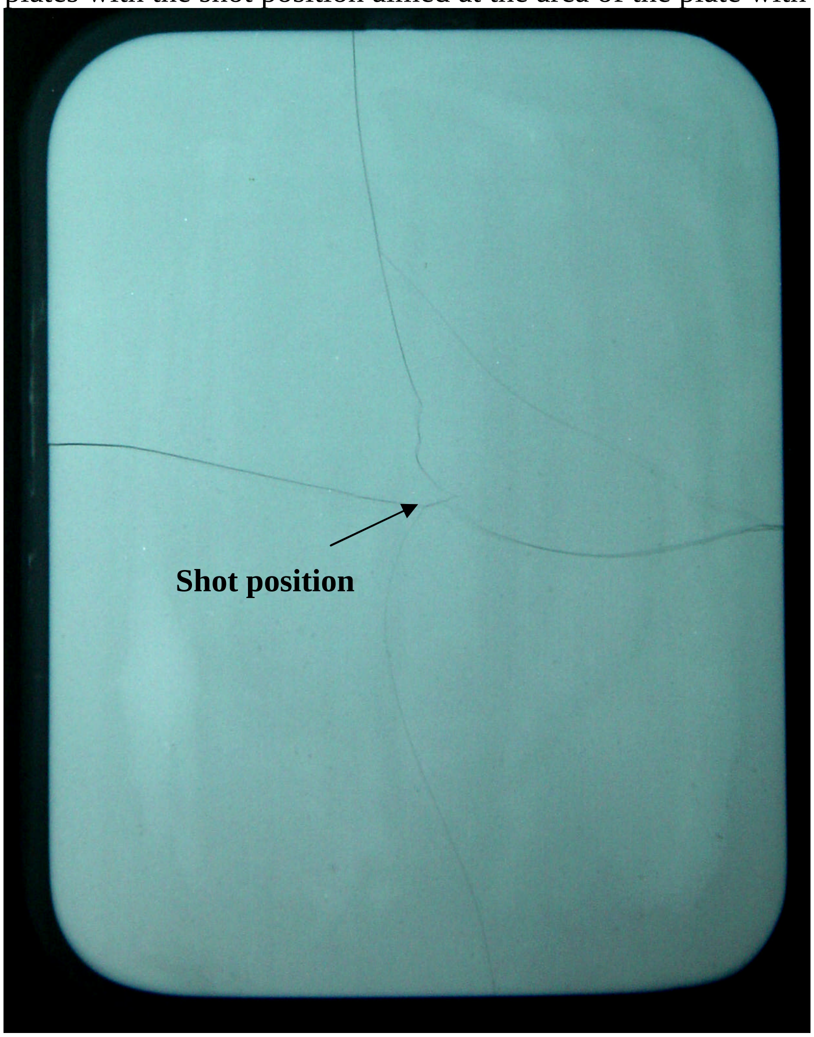

Figure 2. X rayed Armour plate showing induced pre-cracks and shot position

Figure 3. Examples of cracked plates (after test) showing transfer pattern of crack markings and shot aiming positions.

Following this trial, batches of plates from earlier production years were X-rayed before V_{50} ballistic testing to confirm the condition of the plates, batches 5 and 6. The majority of plates classified as A1 from these batches showed no evidence of either severe or hairline cracks. However the X- ray examination confirmed that a small proportion of the oldest plates (batches 5 and 6) had some very light hairline cracking and that these were difficult to detect when visually inspected These plates were separated from A1 condition plates and a V_{50} obtained for each, see batches 5 & 6 in table 1.

Table 1 Effect of cracking on V_{50} trial results

Batch number	Plate Condition	Performance above specification (%)	% change in mean V_{50} ms^{-1} A1 compared with cracked
1	A1	24%	
	'pre-cracked'	15%	-7.2%
2	A1	24%	
	'pre-cracked'	15%	-7.7%
5	A1	20%	
	cracks detected by X-ray	10%	-8.5%
6	A1	16%	
	cracks detected by X-ray	12%	-3.9%
Reject plates	Damage clearly visible	12%	

The results showed that the plates with very fine cracks still performed 10-12% above the specification, but had a 4-10% reduction in V_{50} when compared to A1 condition. Pre-cracked plates performed 15% above the specification with a 7-8% reduction in the mean V_{50} performance of each batch of pre-cracked plates compared with A1 condition. The damaged areas of a batch of plates that had been classified as rejects and exhibiting clearly visible damage were also tested. These plates also performed 12% above the specified performance level. A statistical analysis of all the plates in the trial was carried out on the data, to enable the prediction of levels of confidence, based on the variability in performance against perforation and variations due to batch type.

Theoretical Statistical Model of plate data

A statistical approach was used to model the behaviour of the plates and to provide statistically reliable data on the V_{50} and proof velocity. The analysis used the standard statistical method of a generalised linear model with binomial errors and logit link function (also referred to as logistic regression). This allows probabilities to be predicted as a function of a set of input variables. Fieller's method can then be used to estimate, and produce a confidence interval for the V_{50}, V_{05} and V_{95} [4,5,6]
Figure 4 shows a graphical representation of the probability of penetration as a function of normalised velocity for all the tile batches, with the normalised specified velocity limit

equal to 1. It was found that the statistical model of plate performance gave a graphical output comparable to the Critical Perforation Analysis (CPA) proposed by Gotts *et al* [7]

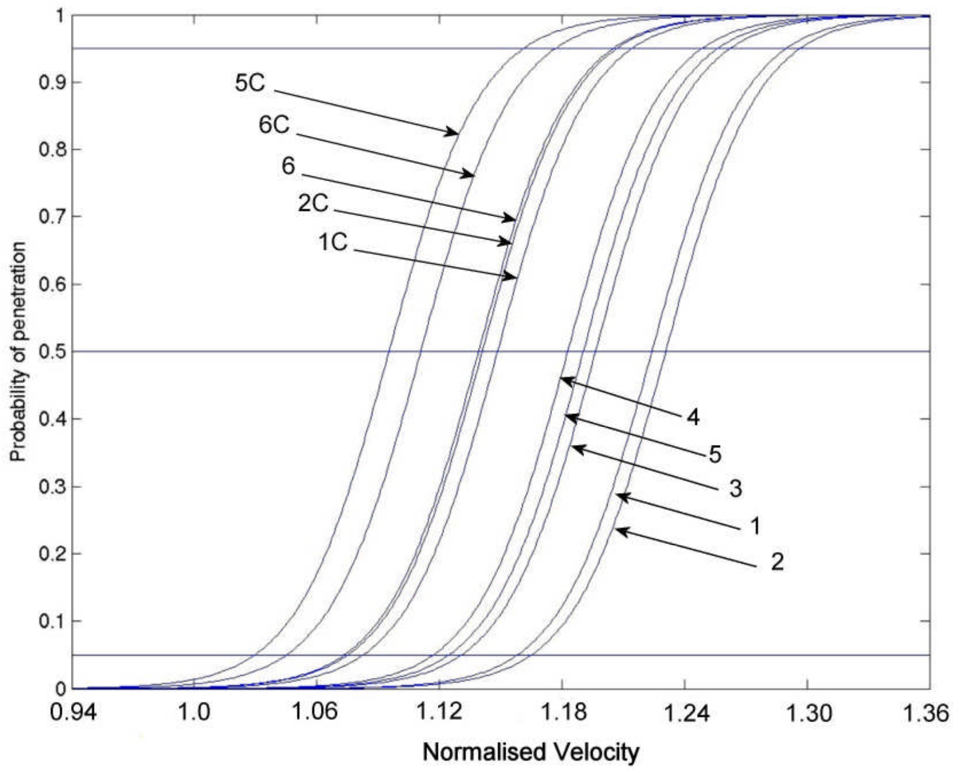

Figure 4. Fitted models of probability of penetration vs velocity normalised with the specified velocity limit equal to 1

This data was tabulated (table 2) in order to illustrate the confidence limits for V_{50}, V_{05} and V_{95}. In this case the V_{05} is important as it predicts the velocity at which there is only a 5% chance of penetration. It can be seen that for all tile batches, cracked or A1 the V_{05} is above the upper limit of the proof velocity. It must be emphasized that the V_{05} and V_{95} are extrapolations from the collected test data which was primarily close to the V_{50}. Consequently the confidence limits on the V_{05} are relatively large. The 95% confidence limits (i.e. the range within which we are 95% certain the true value lies) are tabulated for V_{05}, V_{50} and V_{95}. It can be seen that not only do the V_{05} values all lie above the proof test velocity but that in only one case does the 95% confidence limit of the V_{05} drop marginally lower than the proof test velocity. In practice it is unlikely that performance of the panel will drop below the proof test velocity. However, the model predicts that statistically we cannot be (95%) sure that there would only be a small (5%) chance that penetration would occur.

Table 2. Confidence limits for the values of calculated V_{05}, V_{50} and V_{95} ms^{-1}

Batch No C = cracked		V_{05} and 95% Confidence limits			V_{50} and 95% Confidence limits			V_{95} and 95% Confidence limits		
	n	Lower limit	V_{05}	Upper Limit	Lower limit	V_{50}	Upper Limit	Lowe r limit	V_{95}	Upper Limit
6C	6	0.98	1.05	1.09	1.07	1.12	1.16	1.14	1.18	1.25
6	18	1.01.	1.08	1.11	1.11	1.15	1.17	1.19	1.21	1.26
5C	7	0.96	1.03	1.07	1.06	1.10	1.14	1.13	1.17	1.23
5	15	1.07	1.13	1.16	1.17	1.20	1.23	1.24	1.27	1.33
4	8	1.05	1.10	1.16	1.15	1.19	1.23	1.22	1.26	1.32
3	23	1.08	1.14	1.16	1.18	1.21	1.23	1.25	1.27	1.33
1C	21	1.03	1.09	1.12	1.13	1.16	1.18	1.19	1.22	1.28
1	21	1.11	1.17	1.19	1.21	1.23*	1.26	1.28	1.30	1.35
2C	21	1.02	1.08	1.11	1.10	1.15	1.17	1.19	1.22	1.27
2	24	1.12	1.17	1.20	1.22	1.24*	1.26	1.28	1.31	1.37

For example, the normalised V_{50} for cracked plates is 1.1 of the specified velocity range with 95% confidence that the true V_{50} lies between 1.06 and 1.14. The graphs of the fitted model in figure 4 show that older and cracked plates have lower estimated V_{50}'s than later batches, while the confidence intervals in table 3 show the degree of uncertainty attached these estimates. For example, in table 3 the un-cracked plates from batch 2* have a slightly higher estimated V_{50} than those from batch 1*, (*highlighted in table) but the overlap of their confidence limits shows that this apparent difference is probably due to chance. However, both have higher true V_{50}'s than plates from batch 6 cracked or un-cracked.

Confidence intervals are narrower for batch/crack combinations with larger data sets as its effect can be estimated more precisely. The confidence intervals for the V_{05} and V_{95} are wider than those for the V_{50}'s. The reason for this is that the data were collected according to the UK/SC/5449[3] method for estimating V_{50}'s, which mean that in order to establish a V_{50} the majority of the shots were at velocities close to the V_{50}. Because of the large data set at velocities close to the V_{50}, the estimates and confidence intervals for the V_{50}'s are accurate as these are based on interpolation. However, the low number of data collected for some of the tests on cracked plates, e.g. 6C which had only 6 data points grouped around the V_{50}, (highlighted in column n in table 3) meant that in these cases the V_{05} and V_{95} predictions were extrapolations beyond the range of velocities used in the trial.

Conclusions

It was shown that both the A1 condition and pre-cracked plates from all year batches would meet the current UK/SC/4898[1] specification.

The statistical analysis found that irrespective of plate condition (A1 or cracked) for most batches the (V_{05}) is above the specified velocity limit. For the pre-cracked batches 6 and 5, the 95% confidence limit for the predicted figure does fall below the limit but it is likely that the accuracy of this confidence interval is affected by the low number of shots fired.

Older batches of plates (3 to 6) had a slightly lower performance than more recent batches (1&2). However, it was also found that more than one type of ceramic had been used within these batches, therefore some variability between manufacturers and type of ceramic may account for the slight difference in performance.

A1 condition plates found to have slight or hairline cracks when X-rayed before testing met the specification, but had a 4-10% reduction in V_{50} when compared to A1 condition plates without any imperfections. The reduction in mean V_{50} performance pre-cracked plates when compared with A1 varied from 3.9% for the oldest (batch, No 6) to 7.7% for one of the most recent (batch No 2). However, irrespective of crack type, the ballistic performance of cracked plates remained at least 10% above the specification V_{50} velocity.

X-ray examination has shown that it will accurately detect the presence of cracks so therefore verify the true condition of the plates. However, boundary conditions need to be established for rejection, as plates with cracks were shown to meet the requirements of UK/SC/4898[1].

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Appendix B

ERGONOMIC ASSESSMENT OF MILITARY BODY ARMOUR

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ERGONOMIC ASSESSMENT OF MILITARY BODY ARMOUR

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INTRODUCTION

The human factors (ergonomics) aspects of body armour have not become more important in recent years – they have always been important – but their quantification has been paid increasing attention. There have, for example, been more human factors related papers presented at the last two Personal Armour Systems Symposia (in 2004 and 2006) than in all of the five previous symposia. Studies such as those by Kistemater et al (2004) and Ashby et al (2004) show that wearing body armour can decrease a soldier's mobility which puts the soldier at more risk of becoming a casualty when under fire. The advantage of increased protection can therefore be nullified by a body armour with excessive weight and discomfort.

The Defence College of Management and Technology (DCMT) at Shrivenham has started a new Intermediate Command and Staff Course (Land) to prepare Majors in the UK Army for future appointments. This ICSCL(L) course contains a Survivability module within which there are 'Capability Practicals' to reinforce the content of lectures. One of these Capability Practicals is a 'Combat Body Armour (CBA) Ergonomics' exercise designed to explore issues related to the ergonomics of wearing body armour. This paper discusses the planning, conduct and results of this practical within which about 350 UK army officers performed militarily relevant exercises whilst wearing body armour.

PLANNING OF THE CBA ERGONOMICS CAPABILITY PRACTICAL

Within the Survivability module Capability Practical programme each student (in groups of up to 20) attends five successive 40 minute sessions, the CBA Ergonomics practical being one of these sessions. It was considered that the CBA Ergonomics practical should

- be participative and enjoyable

- (by the end of the practical session) make each student think about the ergonomic penalties of wearing body armour and to be aware that not all armours are the same in this respect i.e. to provide instant feedback

- produce data (ideally quantitative) which, when it accumulated for all the students, can be analysed and written-up with some discussion for transmission to all students i.e. to provide more extensive feedback, say a week after the practical

Military officers who attend the ICSCL(L) course can be expected to take part in physical exercise which is reasonably demanding but there are health and safety implications of conducting a CBA Ergonomics practical which must be taken into account. It was decided, for instance, that the activities should not be timed because that would potentially introduce a competitive element into the proceedings. Also, with the need to process a large number of students in a short time (up to 100 in each set of 5 successive sessions), there would be no opportunity to use complex recording or instrumentation to measure characteristics such as heart rates or temperatures. With time needed for instructional and a health and safety briefing, the tasks would have to be simple and achievable. These decisions meant that it would not be possible to produce quantitative data. Instead, the assessments of the tasks and the armours would primarily to be based on the participants' opinions recorded on a questionnaire (Figure 5).

The tasks which were selected to constitute the practical session were based on a number of factors: practicality, variety and military relevance. The latter requirement ruled out the direct use of some of the ergonomic assessment tasks included in the proposed European Standard for body armour (Comité Européen de Normalisation, 2002). Although this standard has been abandoned, the ergonomic assessment tasks contained therein provide a reasonable basis for a simple qualitative evaluation of the human factors aspects of body armour. Tasks such as 'office use and freedom of movement while seated' may be of limited military relevance though other tasks such as 'standing with arm movements' and 'lying down and getting up' are applicable to soldiers. Tasks such as those described by Ashby et al (2004) which include 'fire and manouvre' and a 'fireman's carry' have direct military relevance but these exercises would have to be adapted if they were to be used in this Capability Practical. A number of activities requiring strength or dexterity were considered for inclusion. The four tasks finally chosen: a 'leopard' crawl, a fireman's lift and two tasks in a Bedford 4 ton truck are described in detail in the next section.

The practical was related to the performance of tasks whilst wearing body armour. Ideally, each participant would have performed each of the tasks without wearing body armour and whilst wearing a number of different armours. The time constraints of the practical however meant that each individual could perform the tasks only twice and it was considered that it would be of more interest and benefit to the participants if they could wear two different armour systems. Other questions arose regarding what if any other equipment should be worn or carried e.g. helmet, individual weapon and additional loads. It was decided it would be logistically much easier if only the body armour were to be worn (over the standard Combat 95 dress which was worn for all the capability practicals). It is pertinent at this point to remind readers that the prime aim of the practical was to increase the awareness of the students about the ergonomics of body armour and not to perform the tasks in a realistic scenario or to fully compare different armours.

CONTENT AND CONDUCT OF THE CBA ERGONOMICS CAPABILITY PRACTICAL

Each student did four exercises (tasks). These tasks were as follows:

20m Leopard Crawl

The leopard crawl, shown on the left in Figure 1, is done using the elbows or forearms to maintain a low silhouette. The upper body twisting movements provide a measure of any restrictions caused by the body armour.

Figure 1: Leopard Crawl and Casualty Drag

20m Casualty Drag and Fireman's Lift

The second planned task was a casualty drag, shown on the right in Figure 1, in which a sand-filled sack weighing about 70kg was dragged along a 20m length of matting. This task proved to be quite simple and with such a short pull, it did not provide any a good assessment of the effects of wearing body armour. So, starting with the second set of practical sessions, a Fireman's Lift was done instead. Each student lifted a punch bag weighing about 70kg onto his or her shoulders and then carried it down the 20m course. The body armour being worn affected the ease of carrying and, in particular, lifting the 'casualty'.

Bedford Climb

Two exercises were conducted using a 4 tonne Bedford truck. The first of these tasks, shown in Figure 2, involved the student climbing up into the back of the truck (a height of over 1.5m) and then lowering himself (or herself) from the side of the truck. The ease of doing these tasks was affected by the weight and encumbrance of the body armour.

Figure 2: Bedford Climb

Figure 3: Bedford Twist

Bedford Twist

The second Bedford truck exercise, shown in Figure 3, was conducted in the cab of the vehicle. This involved climbing into the cab and sitting in the driver’s seat, twisting to put a 'weapon' behind the seats, moving to the other seat and twisting to retrieve the weapon before getting out. The ‘simulated weapon’ was just a metal tube but it was of similar weight and required similar movements to those of a real individual weapon. The twisting movements involved in this exercise provided a good test of any encumbrance caused by the body armour, particularly with regard to arm movements.

Body Armours Worn

In planning this CBA Ergonomics practical, it was desirable that the participants should be able to compare different body armours. However, it was appreciated that a direct comparison of armours designed for the same purpose would not be possible. All participants performed the set of four exercises wearing the standard UK military Enhanced Combat Body Armour (ECBA). ECBA is a front-opening vest which contains high-velocity bullet (HV) protective plates in chest and back pockets. A typical weight of such a vest is 4.8kg. Most participants also performed the exercises wearing a new ‘Top

Cover' variant of ECBA which weighs about 7.6kg. This variant, which is shown in Figure 4, has additional protection to the arms and neck and is particularly intended for vehicle-borne operations. Some officers wore US Interceptor Outer Tactical Vests purchased from a US manufacture which, with the addition of UK origin HV protective plates, weighed 9.0kg or a side-opening Dutch combat body armour weighing 8.4kg.

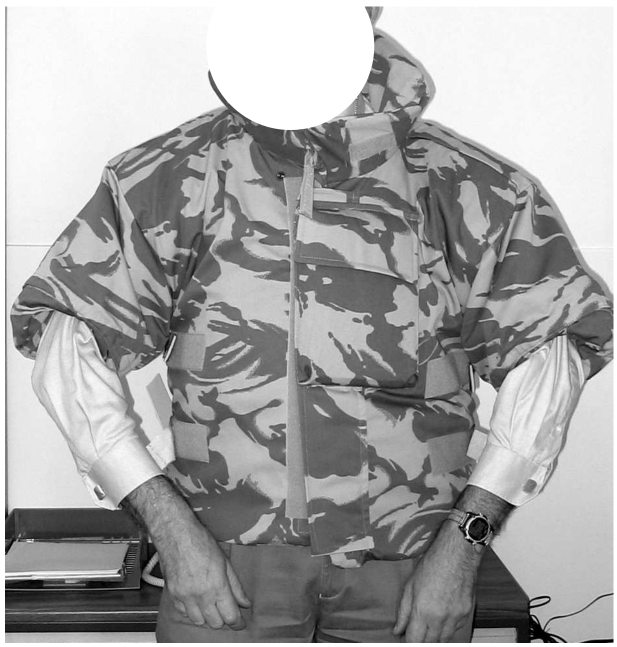

Figure 4: UK 'Top Cover' Body Armour

Conduct of the Practical

For each practical session, up to 20 students were divided into two groups. One group donned one type of body armour (e.g. ECBA) and started the tasks in the Bedford truck. The other group donned different body armour and started the leopard crawl and fireman's lift. The two groups then swapped to complete all four tasks before doffing their armour, donning a different body armour type and doing the four tasks again. Most participants did the practical wearing the ECBA and Top Cover armours. A few, by personal preference, chose to wear the Dutch or US armours (only two sets of each of these armours were available). Any student who expressed reservations about their participation in some or all of the tasks for medical reasons was excused.

After they had completed all the tasks with two different body armours the students were each asked to complete a questionnaire (shown in Figure 5) In this questionnaire they compared the difficulty of each of the tasks and rated five features of each of the armours they had worn. They also indicated if they were male or female but they were not asked for any other personal details. It was observed that performing the more demanding physical tasks such as the Fireman's Lift was easier for those with a larger physique so, in retrospect, some indication of stature and physique would have been useful. In addition to ticking boxes in the questionnaire, many participants added comments about the armours, particular in relation to their use in real military scenarios.

RESULTS

As discussed above, a Casualty Drag was used instead of a Fireman's Lift during the first set of practical sessions when insufficient Top Cover armours were available. For that reason, the results in Tables 1 to 3 include the results from only the following three sets of practical sessions. Table 1 shows how often the different tasks were rated (from the questionnaire in Figure 5) as the easiest or the most difficult.

Sex	Rating	Fireman's Lift	Leopard Crawl	Bedford Climb	Bedford Twist
Male	Easiest	33	35	108	22
	Most Difficult	56	82	12	62
Female	Easiest	1	5	10	5
	Most Difficult	7	7	2	3
Combined	Easiest	34	40	118	27
	Most Difficult	63	89	14	65

Table 1: Rating of Tasks in CBA Ergonomics Practical

CBA ERGONOMICS CAPABILITY PRACTICAL QUESTIONNAIRE

Male ☐ **Female** ☐ (please tick as appropriate)

Which of the tasks was (tick one box in each column)

Most difficult	**Easiest**	
☐	☐	Casualty drag
☐	☐	Leopard crawl
☐	☐	Bedford climb (back of truck)
☐	☐	Bedford twist (in cab)

Which two armours did you wear?

A ☐ **B** ☐ **C** ☐ **D** ☐ **E** ☐ **F** ☐

What characteristics of the two armours did you like and dislike?

Armour ☐	**Armour** ☐
Ease of putting on/taking off Easy ☐ Fair ☐ Difficult ☐	**Ease of putting on/taking off** Easy ☐ Fair ☐ Difficult ☐
Fit Good ☐ Fair ☐ Poor (e.g. chafes) ☐	**Fit** Good ☐ Fair ☐ Poor (e.g. chafes) ☐
Flexibility Good ☐ Fair ☐ Inflexible ☐	**Flexibility** Good ☐ Fair ☐ Inflexible ☐
Weight Light ☐ Medium ☐ Heavy ☐	**Weight** Light ☐ Medium ☐ Heavy ☐
Comfort Good ☐ Acceptable ☐ Uncomfortable ☐	**Comfort** Good ☐ Acceptable ☐ Uncomfortable ☐

If you have time you may wish to add additional comments overleaf related to

- **This capability practical**
- **The armours you wore**
- **Your previous experience with body armour**

Figure 5: CBA Ergonomics Capability Practical Questionnaire

The rating of the armour features is shown in Table 2. The total number of ratings for each armour in this table reflects the number of times that each particular armour was worn. For the reasons explained above, results for the first set of practical sessions are not included. Table 3 shows the results of Table 2 expressed in percentages i.e. it gives the ratings in terms of the percentage of wearers who expressed each opinion.

Characteristic	**Rating**	**UK ECBA**		**UK 'Top Cover'**		**US Interceptor**		**Dutch CBA**	
		M	**F**	**M**	**F**	**M**	**F**	**M**	**F**
Ease of Donning and Doffing	Easy	170	16	38	6	13	1	16	2
	Fair	23	2	116	7	15	1	15	0
	Difficult	1	0	41	5	3	0	1	0
Fit	Good	142	15	68	2	14	1	22	2
	Fair	44	1	103	8	10	1	9	0
	Poor	7	2	23	8	3	0	1	0
Flexibility	Good	152	16	12	0	9	2	17	2
	Fair	33	2	106	12	12	0	15	0
	Inflexible	8	0	78	6	6	0	0	0
Weight	Light	129	9	6	1	0	0	7	0
	Medium	64	9	142	11	19	2	20	2
	Heavy	1	0	47	6	8	0	5	0
Comfort	Good	124	12	28	2	9	1	24	2
	Acceptable	69	6	146	10	16	1	7	0
	Uncomfortable	1	0	25	6	2	0	1	0

Table 2: Ratings of Armours Characteristics by Number of Wearers

Characteristic	Rating	UK ECBA		UK 'Top Cover'		US Interceptor		Dutch CBA	
		M	F	M	F	M	F	M	F
Ease of Donning and Doffing	Easy	88	89	19.5	33	42	50	50	100
	Fair	12	11	59.5	39	48	50	47	
	Difficult			21	28	10		3	
Fit	Good	74	15	35	11	52	50	69	100
	Fair	22.5	1	53	44.5	37	50	28	
	Poor	3.5	2	12	44.5	11		1	
Flexibility	Good	79	16	6		34	100	53	100
	Fair	17	2	54	67	44		47	
	Inflexible	4	0	40	33	22			
Weight	Light	66.5	9	3	6			22	
	Medium	33	9	73	61	70	100	62.5	100
	Heavy	0.5	0	24	33	30		15.5	
Comfort	Good	64	12	14	11	34	50	75	100
	Acceptable	35.5	6	73	56	59	50	22	
	Uncomfortable	0.5	0	13	33	7		3	

Table 3: Percentage Ratings of Armours Characteristics

DISCUSSION

The main aim of the CBA Ergonomics Practical was to raise the awareness of the participants in the human factors aspects of body armour. As such it can be deemed a success. In reviewing the attached results presented in Tables 1 to 3, it should be borne in mind that the participants varied widely in size and shape whereas there was little choice of armour size and fit.

Although all participants took the practical seriously some were more competitive than others and some were physically stronger or were more highly skilled. The influence of skill was noted in performing the leopard crawl or in hoisting the punch bag onto the shoulders for the fireman's lift, though the latter was also affected by strength. Some of smaller and lighter students found the fireman's lift to be very difficult whereas a few large students could toss the punch bag onto their shoulders with consummate ease. The 'Bedford twist' was the only real test of flexibility and it is interesting to note that female students generally found it relatively easy to twist around in the cab to place and recover their 'weapon'. Females may (as a gross generalisation) be more adept at twisting than males but not as big and strong – hence their difficulty with the fireman's lift. A number of the participants felt that it would have been more realistic to conduct the tests whilst wearing a helmet and that a simulation of weapon firing would have been useful.

It should be emphasised that the tests were not intended as a means of comparing the armours. The different armours were not of equivalent fit, or level and coverage of protection. Most of the participants had previously worn ECBA for extended periods and the fact that they were used to this armour was of clear benefit. This helped ECBA to generally score well in the measures of wearability. It should be noted that the extent of HV protection in ECBA is less than that provided in the US and Dutch armours. A number of participants expressed a desire for larger plates. Larger plates however lead to an increase in weight and a decrease in flexibility and therefore a deterioration in wearability. The increased protection has to be balanced against a reduced mobility, a compromise which depends on the nature of a soldier's task. (Ashby et al, 2004). The increased weight of the US and Dutch armours was noticed but, apart from occasional problems arising from the length of the large plates, the comfort was acceptable. The side-opening 'tabard' design of the Dutch armour was well regarded.

The UK 'Top Cover' armour is intended for specific roles and so a like-for-like comparison with the other armours is not fair. However, led in part by the efficacy of modern body armours in protecting the torso, there is a general desire to increase the area of coverage of body armour systems to at least partly include the extremities. So the human factors aspects of body armours with extended coverage is important. The top cover armour made all of the tasks more difficult though the carrying part of the fireman's lift exercise was made more comfortable by the padding provided around the shoulders. The advantages of neck and shoulder protection in the top cover role was recognised though there were some concern expressed that the use of individual weapons could be compromised by the consequent restrictions of movement. These comments were immediately fed back to the manufacturer and modifications to the armour have subsequently been made. Although not a direct aim of the capability practical, it resulted in the concerns about restrictions of movement during weapons handling being addressed promptly by the manufacturer.

The practical was successful in bringing out some of the human factors issues of wearing body armour. The participants, most of whom had had direct experience of military conflict, were generally in favour of increased protection but they appreciated the need for compromise. The body armour designer aims to maximise the degree and the extent of the protection given by the armour but to do so without prejudicing the activities of the armour's wearer. The tasks themselves and the time spent thinking about these issues during the CBA Ergonomics Capability Practical helped a set of body armour users to better appreciate the body armour designer's dilemma.

ACKNOWLEDGEMENTS

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Appendix C

ASSESSMENT AND MEASUREMENT OF POTENTIAL BLUNT TRAUMA UNDER BALLISTIC HELMETS

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This paper investigates measurement techniques to evaluate ballistic impact protection in terms of head contact loads from non penetrating impacts on helmets. An aluminium head form instrumented with piezo-electric transducers, film sensors and accelerometers was used to measure impact forces applied by the back face deformation of helmets after ballistic impacts. The head form and an instrumented accelerated weight machine are also used to measure impact forces applied to the helmet and forces transmitted behind the helmet.

Radius of curvature of back face deformation data were also collected from ballistic impacts on helmets mounted on conditioned plastilina® and was shown to correlate with published studies from Wilber [4] and Byers [5] which established a correlation between the force required to fracture a human skull and radius of curvature of the striker. It is shown that backface deformation of potentially damaging levels can be generated behind typical ballistic helmets.

Keywords: Blunt trauma, Helmets, Ballistic protection

INTRODUCTION

The purpose of this study was to measure impact forces with different sensors in attempt to determine whether a relationship from the back face forces resulting from non penetrating impact and the forces required for injuries to the skull or brain can be found. The aim of the work was to evaluate these impact forces and use the information to further the development of a robust method of force measurement for helmet testing.

Bullet impacts transfer kinetic energy onto a small area and whilst a helmet may prevent penetration of the skull and brain from the ballistic impact, back face deformation (BFD) of the helmet could result in high contact loads to the skull causing shock waves and consequently serious head injuries. The relationships between behind helmet impact forces, energy and brain injury have not yet been defined.

PRELIMINARY TRIALS

Forensic analysis by Wilber[4] and reported by Byers[5] has established a relationship between the amount of force necessary to cause a skull fracture from the deformation found on the frontal bone. Wilber[4] related the size and shape of the permanent damage left by compressive fractures after fatal attack by blunt weapons such as hammers to the radius of curvature of the impacting weapon, figure 1.

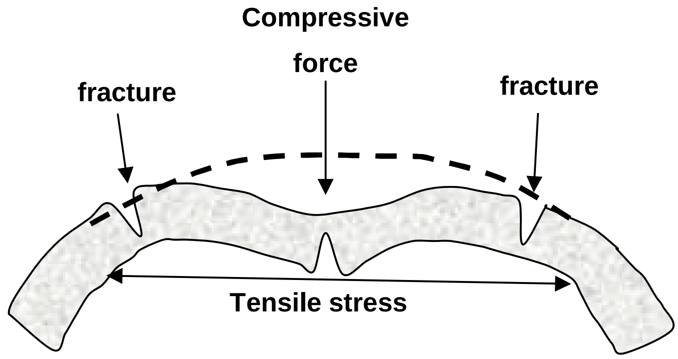


Figure 1. Skull fractures induced by impact force (after Byers [5])

A program of ballistic trials was carried out to investigate if the radius of curvature from back face deformation caused by blunt weapons described by Wilber[4] could also be extrapolated to ballistic impact on helmets. Preliminary ballistic trials with 9mm DM11A1B2 ammunition fired from a proof barrel at 5 metres were carried out. To ensure that the ballistic impacts caused measurable BFD in these initial trials aramid helmet shells without impact mitigating materials such as trauma padding or specialist carriage systems were used. The velocity range was 283 - 459 ms^{-1} all bullets were stopped and significant measurable back face deformations were seen.

Following the above trial, plastilina® pre-conditioned and calibrated as in a ballistic body armour test was chosen as a suitable witness material to back the helmet shells and measure the radius of curvature of the indents behind the helmets. Trials at the velocities that had produced measurable back face deformations with 9mm DM11A1B2, 30cal and 50cal fragments were carried out on the helmet shells. The indentations in the Plastilina® were measured and the radius of curvature estimated. These tests were repeated with a set of helmets with mitigating padding and fitted carriage systems and figure 2 shows the test results plotted and superimposed on the forensic data graph.

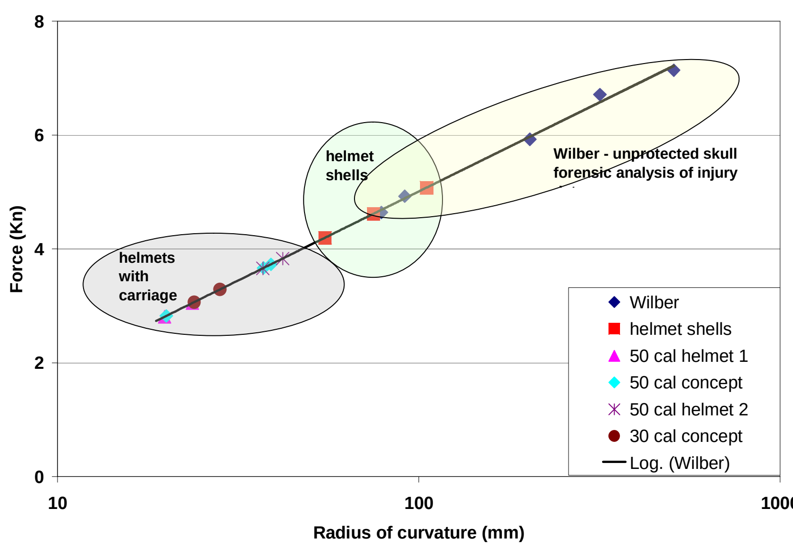
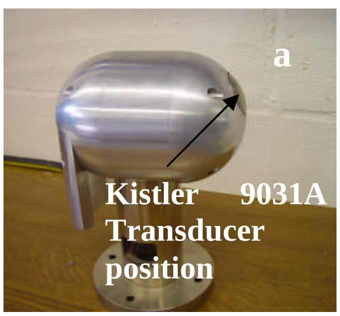


Figure 2 – Force vs Radius of Curvature for Skull Fractures

When compared with the skull fracture loads reported by Wilber[4] the radii of curvatures measured from the ballistic impacts corresponded to force values of 4 to 5kN, figure 2. These force values and an average head weight (mass) of 5kg were used to derive acceleration ($F = m \times a$) which was found to be 100g. This result implies that the skull could be fractured by BABT with accelerations of approximately 100g supporting Slobodik[6] whose investigation into US Army helicopter crashes concluded that the 400g limit of acceleration for survivability should be reduced to 150g.

HEAD FORM DEVELOPMENT AND CALIBRATION OF SENSORS

To quantify and measure the impact forces a simple aluminium head form shape was fitted with a 9031A Kistler® force transducer and film sensors, figure 3a and 3b. These film sensors are very reasonably priced so for testing could be considered



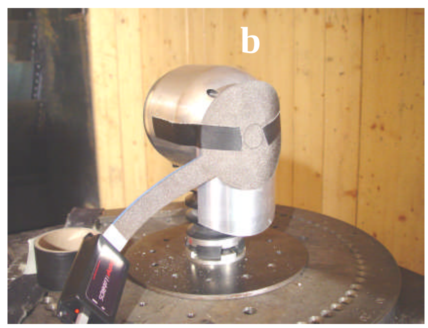
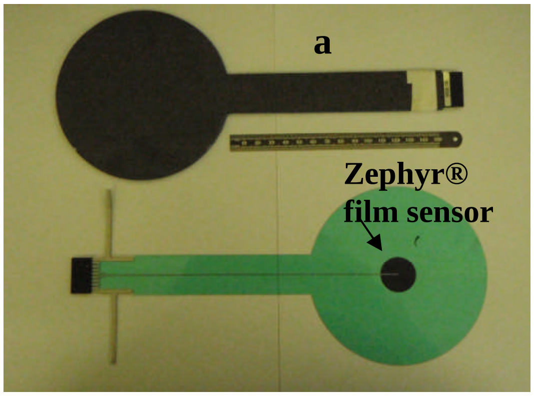


Figure 3. (a) Aluminium head form (on stand) showing position of Kistler® transducer b) Sensor attached to Aluminium head form and Hybrid 3 neck

as a one test disposable item. The film sensors were more flexible and easy to attach to the head with tape. It was hoped that the film sensors would be able to pick up an average force for over a fixed area throughout the impact event. The 25mm sensor pad is positioned in the centre of a flexible polymer film sandwiched between two layers of foam. The sensor samples at 250 kHz in 30ms and the output is an average of the applied force across the sensor. To validate the force output from these sensors a calibration method was developed their outputs were compared with the force output from a calibrated[6] 9031A Kistler® compression load cell fitted into an Imatek IFW10 accelerated drop weight machine, figure 4a and 4b.

To compare and understand the effect of averaging of the applied force over an area three striker shapes were used to investigate the application of load over different surface areas. In the initial tests an aluminium base plate simulated the effect of the aluminium head form which would be used in the ballistic tests. Force, time, velocity and displacement during an impact event are measured by the Imatek IFW10 and as the mass of the falling weight is known energy to fail can be determined. No electronic smoothing or signal processing filters were applied to the data as these can reduce the peak force values.



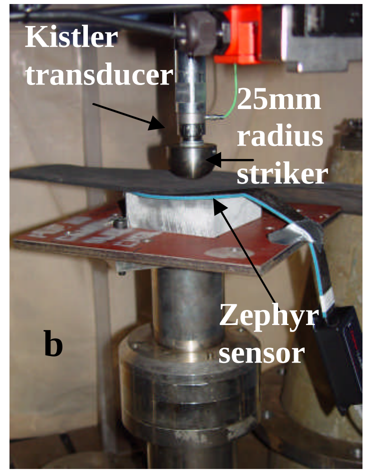


Figure 4. a) Film sensor inner and protective foam cover, b) Striker assemblies and Drop tower calibration set up showing the 50mm radius striker fitted.

The impact velocity for all drop tower tests was 1ms^{-1} and the sensors measured between 50% and 70% of the applied load. This difference may be attributed in part to some of the forces being dissipated by the protective foam layers at either side of the sensor. Peak force values for the 25mm striker were double those for the 50mm and 15mm strikers. The measured force per unit area is averaged by the Zephyr® sensors this indicates that for this striker the impact forces were distributed over a smaller contact area, figure 5. High peak forces over a short time would be expected from ballistic impact upon a helmet, therefore this striker was selected for calibration of the outputs from Zephyr sensors, transducer and accelerometers in the head form.

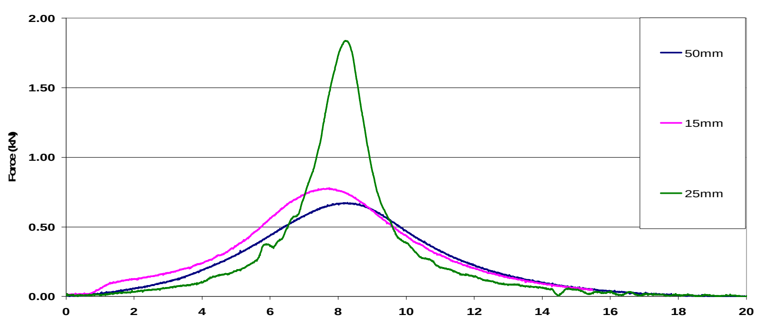


Figure 5. Comparison of Force vs Time drop tower traces of the three striker shapes

CALIBRATION OF THE HEAD FORM TRANSDUCER

The 9031A Kistler ® transducer in the Imatek IM10 drop tower was used to calibrate the force responses from the Kistler® 9031A transducer fitted into the aluminium head form mounted onto a hybrid III neck, figure 3a. Figure 6 shows the force responses from the head form transducer and these correlated with the force being applied, figure 6.

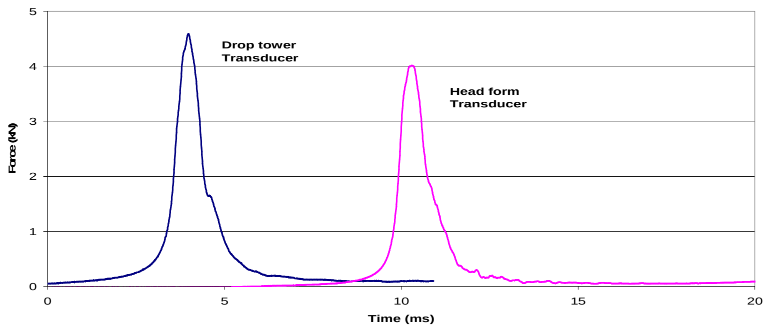


Figure 6. Comparison of force outputs from Kistler® transducer fitted in Imatek drop tower and head form.

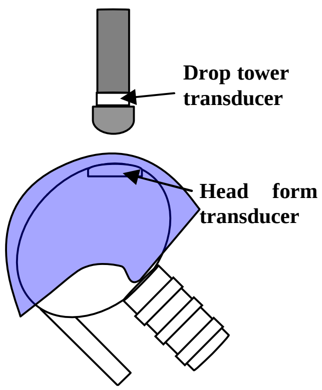


Figure 7. Diagram of head form positioned for drop tower impacts

The drop tower tests continued with helmets fitted onto the head form as illustrated in figure 7, to calibrate the force transducer outputs with the three accelerometer outputs. Using the least squares method the x, y and z axes accelerometer outputs were then summed to give a figure for total acceleration and multiplied by the mass of the head (4.82kg) to derive a force value to check the validity of the outputs from the system.

Figure 8 compares the peak force from the drop tower transducer (the applied force) of 7 to 8kN with the peak force of 1.8kN measured by the head form transducer behind the helmet and shows the effectiveness of the helmet shell and padding in attenuating the force.

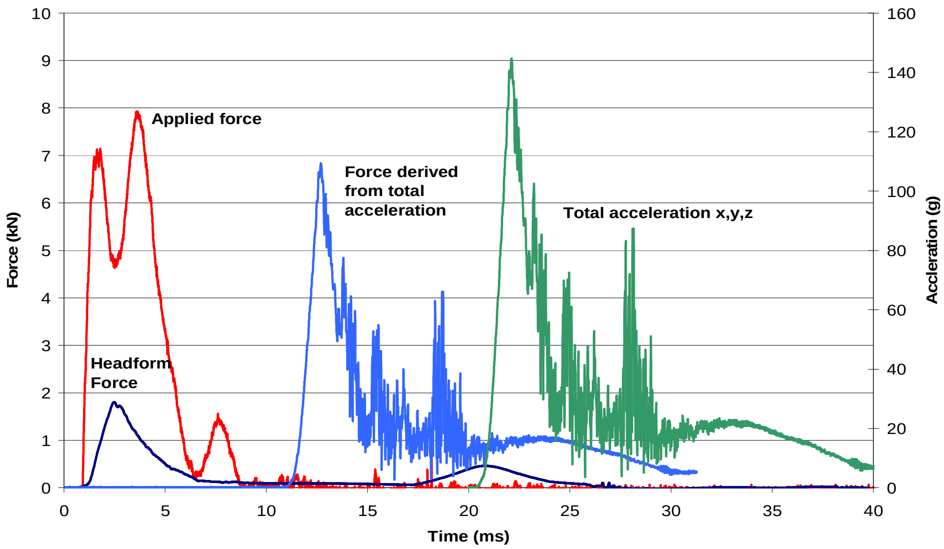


Figure 8. Comparison of Transducers and Accelerometer outputs

The total acceleration of 140g is under 400g limit of acceleration for survivability and correlates with Slobodik[7]. The force trace derived from total acceleration data verifies the applied force data. The time history of this test correlates with that seen in work on blunt impact and the 15-20ms duration of the force pulse is typical of time durations recommended for the calculation of head injury criteria (HIC).

BALLISTIC TESTS

After calibration both the headform transducer and film sensors were used to measure forces and accelerations from back face deformations behind two different helmet types and aramid helmet shells fitted with carriage systems. All shots imparted a load centrally on the sensor. The shots were positioned over the mitigation pads on the front right or front left temple or centre back with this padding in direct contact with the head form. No standoff distance from the head form was allowed and no skin or tissue simulant was placed over the transducer impact area. These test conditions combined with rigidity of the aluminium head form transducer mounting would measure the magnitude of the forces of a "worst case" impact scenario. Without extra foam protection some of the film sensors sustained irreversible damage during ballistic impact so a limited amount of data was collected from those tests. Although the response time of the sensors is fast enough for ballistic impact events the sensors will need further development to improve their robustness during the impact event.

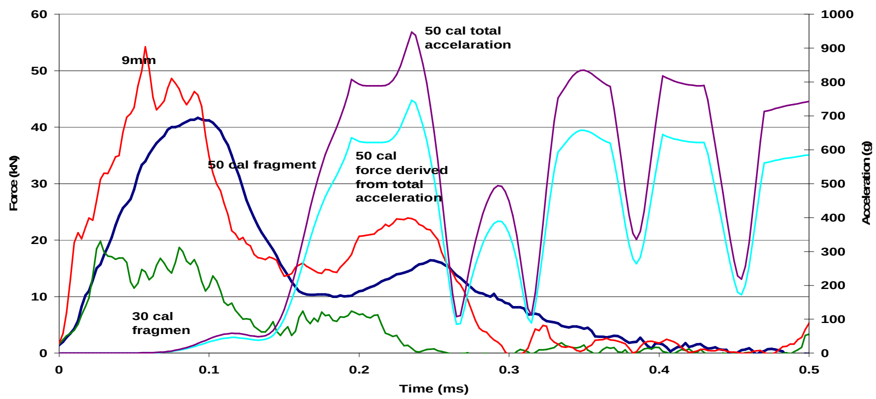


Figure 9. Comparison of force traces from head form transducer of 30 cal, 50 cal and 9mm shots

Force traces from 9mm, 50cal and 30cal fragments impacting the head form transducer and the order of severity of the impacts on helmet shells are compared in figure 9. Each shot was placed on the helmet so that the transducer would be correctly loaded along its centre axis. The smaller 30 cal fragment (2.84g at $473ms^{1}$) imparted an impact energy of 318J and consequently had a lower peak force compared to the 540J from the heavier 50 cal fragment (13.39g at $284ms^{-1}$) and the 666J from 9mm (8g at $408ms^{-1}$) round. The force trace derived from the total acceleration of the 50 cal shot is also shown and verifies the force data from the head form transducer. The force readings recorded from the 9mm and 50 cal impacts are high and the peak acceleration of 940g from the 50 cal impact is more than double the accepted 400g limit. The time to reach peak force and acceleration and the duration of the pulse is short at typically 0.05ms or less. High speed video of the event showed that upon impact the helmet deformed applying a force to the transducer, the helmet material then rebounded and resonated with the oscillations gradually being absorbed by the helmet, head form and neck movement. No acceleration of the neck was seen during the short duration of the ballistic impact event. Measurements from the high speed video showed the acceleration of the head and neck began at 0.69ms. The complete unfiltered time history of the head impact and neck accelerations of a 9mm shot as they gradually decrease over 5ms is shown in figure 10.

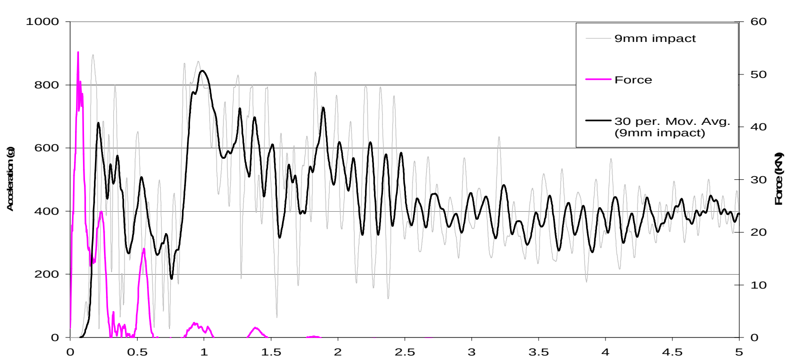


Figure 10. Force vs time and acceleration vs time histories of the head impact and neck accelerations from a 9mm impact

This time history correlates with previous work by Bass et al [1] on 9mm impacts on helmets mounted onto a modified hybrid III head form. A 30 point moving average filter was applied to the accelerometer data to resolve the major peaks in the signal for comparison with the Force signal but the first peak is reduced dramatically by filtering. Low pass digital filtering also reduces peak force levels so the filtering process must be used carefully or meaningful data could be lost.

SUMMARY AND FURTHER WORK

This initial work showed the head form was robust and could be suitable for simple ballistic tests as the peak force results were repeatable. The duration of the time of the ballistic impacts correlated with high speed video and similar work by other research groups[1,2,3] as did the timings to accelerate the neck. The 0.05ms duration of the peak force imparted to the head from ballistic impact is at a much higher rate than the 15.0ms duration rate accepted as suitable for the HIC calculations used for blunt impact. This concurs with Bass[1] who found that current HIC is not the best method to predict likely levels of head injury in ballistic events. Further work will be necessary to investigate compliance issues due to the rigidity of the head form when compared with more biofidelic systems.

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Appendix D

ERGONOMICS OF BODY ARMOUR

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Ergonomics of Body Armour

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Abstract. Increasing the performance levels of body armour often results in armours which have a negative effect on human performance. Ergonomics are accepted as being important but often in the provision of the correct level of protection the ergonomic aspects of body armour have not been fully assessed. Most current body armour standards do not include methods to evaluate ergonomics, only the CEN prEN ISO 14876 Standard includes a method and this standard was rejected in 2002. This work describes the development of trials and methods to evaluate the ergonomics of body armour. Trials were carried out with male and female volunteers, with up to 150 military students per trial from the Defence Academy of the UK and 30 Police volunteers from several UK Police Forces. Activities relevant to Military or Police duties were selected so that the movements assessed a particular characteristic of a body armour system. Several comparative trials with armours were undertaken and will be discussed. After the trials, the wearers completed a questionnaire and their perception of the comfort and wearability of the armours was determined. The trials were designed to be completed in one day with the volunteer sample size being valid for statistical analysis. The questionnaire was a simple one page form completed immediately after the trial. Questions were specifically chosen to evaluate reported problems and carefully worded so the required information was easy to extract. To simplify processing, numerical scores were used for evaluating each task to enable a ranking value to be calculated for each armour type and activity in the trial. The results proved the method was both cost effective and a useful design tool. Simple twisting, bending and arm movements of upper torso highlighted ergonomic difficulties and running on the spot was good for indicating possible chafing points.

Keywords: Ergonomics, body armour, wearer trials.

1. INTRODUCTION

In the past twenty years most of the research into UK Police body armour has been focussed on defining the threat level [1] so that the correct level of ballistic and knife protection is worn. Also in reducing bulk and weight and developing more flexible armour systems. Consequently many body armour solutions are available for a variety of specific threat levels. However, there is less information in the Police sector about what effect wearing armour has on human performance. Recently the interest in the human factors, (ergonomic) aspects of body armour has increased and ergonomics have become an important factor to consider in the design of new armour systems.

Poorly fitting armours with the weight distribution over the body being ‘unbalanced’ can cause chafing. Such armour may also interfere with and effect the operation of other equipment such as batons, radios and handcuffs. This can affect the performance of officers’ during their normal duties, resulting in discomfort which increases irritability and leads to exhaustion.

Standard methods to assess the ergonomics of different armours are not included in many Body Armour Test Standards and of those listed below only the CEN prEN ISO 14876 Standard (2001) - Ballistic Knife & Spike includes a section on ergonomics. This European standard was rejected by CEN in 2002 although the CEN/TC 162/WG 5/PG 5 Committee revisited the Standard in 2008 and are currently (2010) working on a revision.

1.1 International Body Armour Test Standards

UK HOSDB (2007) - Ballistic, Knife & Spike [1]
USA NIJ 0.101.06 (2008)- Ballistic [2]
USA NIJ 0.115.00 (1999) – Stab [3]
NATO STANAG 2920- Ballistic [4]
German VPAM & PTI (2008) - Ballistic [5]
Russian GOST-R 50744-95 – Ballistic [6]
CEN prEN ISO 14876 Standard (2001) – Ballistic, Knife & Spike [7]
German standard DIN 52290 (Technische Richtlinie Schutzwesten) [8]

2. EVALUATION OF POLICE BODY ARMOUR

In the UK the ergonomics of Police body armour has usually been assessed by undertaking a wearer trial. These trials consisted of issuing armour to officers to wear over a period of time typically up to six months, then to complete a questionnaire. Because the trials have taken up to six months or longer they have been expensive. Often after this time period the return of questionnaires was sporadic and the details were often not filled in accurately enough to be useful.

The purpose of this trial was to develop a comfortable wearable system by modifying small numbers of armour at a development stage to avoid costly modifications on large production batches. The ergonomics of different armours would be assessed by performing several 'typical Police tasks' with and without body armour. A trial that could be used as a design tool by assessing the level of difficulty of the chosen tasks whilst wearing different armours would be developed, identifying at an early stage the areas needing improvement.

2.1 Methodology

The focus of designing this trial was to identify body movements that were relevant to Police duties but would also assess a particular characteristic of a body armour system. Ideally the armour systems should not restrict the officer in carrying out his/her duties so normal tasks should be able to be performed. Armour flexibility and discomfort such as chafing and pinching, and irritation were also perceived to be important factors. So to evaluate the ergonomics of the selected armour systems and to compare one armour system with another, a list of movements that could be linked to typical Police tasks was compiled. These movements included the assembly, adjustability and fit of the armour, warm up exercises, some Officer Safety tactics, an evaluation of movements in a vehicle and the wearers' perception of the general comfort and wearability of the armours.

2.2 Test protocol and Questionnaire

The test protocol and a questionnaire based on the movements identified above were approved by the National Policing Improvement Agency, The Metropolitan Police and Cranfield Health Research Ethics Committee before the invitations for volunteers were sent out to the UK Police Forces. It was important that the questionnaire should be a one page form, figure 1. This was to reduce the amount of paperwork so the trial could be completed quickly. As it was also important to get unambiguous data from the trial a simple form was designed with tick boxes and short explanations of a numerical ranking system.

Ergonomic Assessment of Body Armour **Date:** ____

Volunteer Number ☐ **Male** ☐ **Female** ☐ **Amour Name/Type** ____

Please tick one box for each question: 1 = poor, 2 = tolerable, 3 = good, 4 = very good

Assembly and Fitting

Remove armour panels from the carrier, read label, insert into carrier. How difficult are these actions?

	1	2	3	4		1	2	3	4
Is the labelling readable?					Is the armour easy to put on?				
Is the armour easy to put into carrier?					Is the armour easy to adjust to fit?				

Warm up	1	2	3	4		1	2	3	4
Running on the spot					Behind body reach				
Above shoulder stretch					Cross body reach				

	Yes	No		Neck	Armhole	Waist	Shoulder
Did the armour chafe?			If Yes where?				

Officer Safety Tactics

How difficult were the following safety tactics whilst wearing body armour?

	1	2	3	4		1	2	3	4
Knee strikes					Handcuff				
Draw baton closed mode					Prone search tackle bag				
Figure of eight strike					Stow tackle bag				
Extend baton and strikes					Move tackle bag across and out of car				

Vehicle evaluation

How difficult were the following actions in a vehicle whilst wearing body armour?

	1	2	3	4		1	2	3	4
Adjust seat, put on seat belt					Turn head to right, turn head to left				
Take an object out of glove box					General driving				
Maximum extent of reach (mm)									

General

	1	2	3	4
Was the weight of the armour good?				
Was the size and shape good?				
Good compatibility with rest of uniform?				
Was the weight distributed well over the body?				
How comfortable overall was this armour?				
How well does the armour fit?				

	Yes	No		Neck	Armhole	Waist	shoulder
Did the armour chafe?			If yes where?				
or pinch?							

Other comments

Please add any additional comments in the box below

Figure 1. Questionnaire

2.3 Ranking system

To ensure some clarity in the data a marking system of 1-4 points was chosen. With points awarded to grade the armours as follows: 1 = Poor, 2 = Tolerable, 3= Good, 4 = Very good

The purpose of choosing 1-4 was to make a volunteer think carefully about the points he/she had to award for each task and engage with the choice. If a marking system of 1-5 is chosen, with a middle value of 3 for neither good nor bad, there is a tendency for the majority of volunteers to choose the middle value as an easy choice or opinion. This of course does not help the analysis, as it does not highlight small differences between one design of armour and another. The objective was that the marking scheme would produce a high score for well designed armour systems. So a poor design would only score 1 and armour that was tolerable to wear would score 2, indicating that although it could be worn there were areas that still needed improvement.

A spread sheet was compiled to process the data (figure 2) marks were totalled for each task then these scores totalled and divided by the number of volunteers to obtain a simple ranking figure for each system.

Protection levels	HG1A/KR1																								
Activity movement or assessment	1	2	3	4	5	6	7	8	9	10	11	12	13	27	28	29	30	19	22	23	25	14 F	15 F	16 F	17 F
Is labelling clear	3	4	3	4	4	3	3	3	4	3	4	4	3	3	4	4	4	4	4	3	3	3	4	4	4
Easy to put in carrier	3	4	3	4	4	3	3	3	4	4	4	4	3	2	4	4	4	4	4	4	3	4	4	4	3
Easy to put on	4	4	3	4	4	3	3	2	2	4	4	4	4	3	4	4	4	4	3	3	2	4	3	4	4
Adjustment to fit	4	4	4	4	4	3	1	2	1	4	4	4	4	3	3	4	4	3	3	4	2	4	3	4	4
Running on the spot	3	4	4	4	4	2	3	3	1	4	4	4	3	3	4	3	4	4	3	3	1	4	3	4	4
Above shoulder stretch	4	4	4	4	4	2	3	2	2	4	4	4	3	3	4	4	4	4	3	3	1	4	4	4	4
Behind body reach	3	4	4	4	4	2	4	3	1	4	4	4	4	2	4	4	4	4	3	3	2	4	3	4	4
Cross body reach	3	4	4	4	4	2	4	2	1	4	4	4	3	3	4	4	4	4	3	3	2	4	4	4	4
Chafing	4	4	4	4	4	3	3	3	3	4	4	4	4	4	4	3	4	3	4	3	4	4	4	4	4
Knee strikes	4	4	4	4	4	2	3	3	2	4	4	4	4	3	4	3	4	4	3	4	2	4	4	3	4
Draw baton closed	3	4	4	4	4	2	3	3	2	4	3	4	3	3	4	3	4	4	3	4	2	4	4	3	4
Figure of eight strike	3	4	3	4	4	2	4	3	2	4	3	4	3	3	4	4	4	4	3	3	2	4	4	3	4
Extend baton and strikes	4	4	4	4	4	2	4	3	2	4	3	4	3	3	4	4	4	4	3	3	2	4	4	3	4
Handcuff	4	4	4	4	4	2	3	3	2	4	3	4	4	2	4	3	4	4	3	4	2	4	4	4	4
Prone search tackle bag	3	4	4	4	4	2	3	3	2	4	3	4	4	2	4	3	4	4	3	4	2	4	4	4	4
Stow tackle bag	4	4	4	4	4	2	3	3	2	4	3	4	4	3	4	4	4	4	3	3	2	4	4	4	4
Move tackle bag	4	4	4	4	4	2	3	3	2	4	3	4	4	3	4	4	4	4	3	3	2	4	4	4	4
Adjust seat clip seatbelt	3	4	3	4	4	2	2	3	2	4	3	4	4	3	4	4	4	4	3	4	2	4	3	4	4
Retrieve object from glovebox	3	4	4	4	4	1	3	3	3	4	4	4	4	2	4	4	4	4	3	4	2	4	3	4	4
Head turns	3	4	4	4	4	2	2	3	2	4	4	4	3	3	4	3	4	4	3	4	2	4	3	4	4
General driving	3	4	4	4	4	2	3	3	3	4	3	4	4	3	4	4	4	4	3	3	2	4	3	4	4
Weight good	4	4	4	4	4	3	3	3	3	4	3	4	4	3	3	4	4	3	3	3	3	4	4	3	4
Size and shape good	4	4	4	4	4	3	3	3	1	4	4	4	4	2	3	4	4	3	3	3	3	3	2	4	4
Compatibilty	3	4	4	4	4	3	4	3	2	4	4	4	4	3	3	3	4	3	3	4	2	4	3	4	4
Weight well distributed	3	4	4	4	4	3	3	3	2	4	3	4	4	3	3	3	4	3	3	3	3	4	3	3	4
Comfortable	4	4	4	4	4	2	3	2	1	4	3	4	4	2	3	4	4	4	3	3	2	4	3	4	4
Good fit	4	4	4	4	4	2	2	1	1	3	4	4	4	2	3	4	4	4	3	3	2	3	3	4	4
Chafe and pinch	4	4	4	4	4	2	3	3	3	4	4	4	4	4	4	4	4	3	4	3	4	4	4	4	4
neck						0	1	1	1									1		1					
armhole						0	0	0	0									0		0					
waist						1	1	1	1									1		1					
shoulder						1	1	1	1									1		1					
Totals	98	112	107	112	112	64	84	77	58	110	100	112	103	78	105	103	112	105	88	94	63	109	98	106	111

Figure 2. Typical Spreadsheet showing scores

3. ERGONOMIC TRIAL

Invitations for volunteers were sent to UK Police Forces by the National Policing Improvement Agency (NPIA) and thirty volunteers from various Forces were selected. The sample size of thirty was chosen to be a valid number statistically and to compare with the sample sizes of previous trials. Both male and female officers in a range of sizes were chosen from small female to large male. Trained uniform fitters took the volunteers body measurements which were supplied to four manufacturers for armour to be made to ensure a personal fit for each volunteer. These fitters were present at every trial to ensure that each individual had their armour fitted personally. If a size could not be found for a volunteer and they could not be fitted with any one type of the armours in the trial, these volunteers were discounted from the data set collected in the trial. All volunteers in the trial wore each of the armour systems available so a direct comparison of one armour type with another on the day was possible.

Manufacturers were then asked to provide concept body armour carrier systems for use in the trials. As part of the carrier development the manufacturers entered into a consultative dialogue with the Personal Protection Group (PPG) of the Metropolitan Police who offered their expertise in body armour development. They made suggestions and provided useful information on which areas of the armour carriers could be improved based on feedback from wearers of the current Metropolitan Police body armour systems.

The designs of the carriers supplied by each manufacturer were: Manufacturer A incorporated a ribbed nylon fabric at the sides, under the arms and on the shoulders. Manufacturer B had chosen a similar fabric for an inset around the armholes the design had armholes that fitted the around the arm snugly and this carrier also had a higher neck with a narrow integral collar and was slightly lower at the front. Manufacturer C provided an all polycotton carrier that stopped at waist level. Manufacturer D also used ribbed nylon fabric at the sides, under the arms and on the shoulders but with a longer length carrier which looked very smart as part of the Officers' uniform.

The major differences in the carriers were the size of the armholes and neck followed by the length of the carriers. Manufacturer C had the most generous allowance at the armholes which were cut lower than the other two versions. All armours had a front zipper in the carrier to allow the armour to be taken off and put on as a jacket. However the front armour panel is in one piece to provide maximum protection to the front of the body and the methods to secure this panel when the zipper was opened differed between the manufacturers.

3.1 Activities in the trial

3.2 Assembly, adjustability and fitting

After fitting, the officers were instructed to take out the armour panels from their carriers check the labels then insert the panels back into their carrier, adjust the straps and put the armour back on. This was to simulate being issued with their armour and re-assembling after washing the carrier. It is particularly important that the labels on the armour panels are clear and easy to read and the instructions clearly indicate which side of the armour panel is worn next to the body when inserted into the carrier.

3.3 Warm up

Before beginning the movements for officer safety tactics a series of aerobic warm up exercises were carried out under the supervision of an officer safety trainer. These exercises consisted of running on the spot, an above shoulder stretch, behind body reach, in front of body reach and a forward bend. The way in which the armour moved on the body during these exercises was very useful in indicating areas of potential chafing and irritation. Twisting the body during the bending movements was invaluable in determining the amount of flexibility any armour might have.

Figure 3. Warm up exercises and officer safety tactics

3.4 Officer safety Tactics

The officers completed these tactics in pairs beginning with a knee strike onto a pad then the baton was drawn closed from the belt and a forward strike followed by multiple strikes was carried out on the pad. The baton was then replaced on the officers' belt. Following this with one volunteer acting as a suspect a prone search and handcuff manoeuvre was carried out. These movements highlighted potential problems with armour moving on the body and compatibility with equipment that officers wear on their belts.

Then a large tackle bag was manoeuvred into the back seat of car. When in place, the tackle bag was moved across the back seat then out of the opposite car door. This was to replicate some of body movements expected from an officer whilst moving suspects from place to place by car. Observations were taken from how the armour moved with the body and which of the armours rode up and caused discomfort.

Figure 4. Tackle bag manoeuvre and in car movements

3.5 Vehicle Evaluation

To evaluate movements in a vehicle, officers were asked to get into the front drivers seat of a car, adjust the seat and put on the seatbelt. Whilst wearing the seatbelt they were then to take an object out of the glove box. A member of the trials staff measured the distance the officer was able to reach across the car without feeling restricted. Then the volunteers turned their heads as if reversing the car and were asked to assess how their armour effected general driving movements.

3.6 Comfort and Fit

After completing these tasks the volunteers were asked to assess the weight of the armour, its size and shape and how well the weight was distributed over the body. Then to consider how the armour interacted (compatibility) with other items of uniform and the Police equipment they wear everyday. They were asked to fill out a questionnaire before they changed into another armour system. However, at the end of the trial when all armours had been worn they were allowed to amend their ranking if they felt strongly that their views had been changed by wearing another armour system.

4. RESULTS

4.1 Ranking exercise

The aim was to determine if the scoring system could distinguish between the merits of one armour system and another. The information from the ranking exercise in this trial was not intended to be used as pass/fail criteria. The results in figure 5 show that the numerical scoring system was able to highlight armours where more work needed to be done. Of the six armours trialled, the results indicated that armours 1&2 needed little modification, armour 3 required the most modification and 4, 5 and 6 some modification. It is interesting to note that the system could also identify a difference in scoring between females and males. Armour 2 was scored high by all females with the scores for the males similar to those for armours 1 and 4. Generally females found the other armours in this trial less comfortable to wear than their male colleagues.

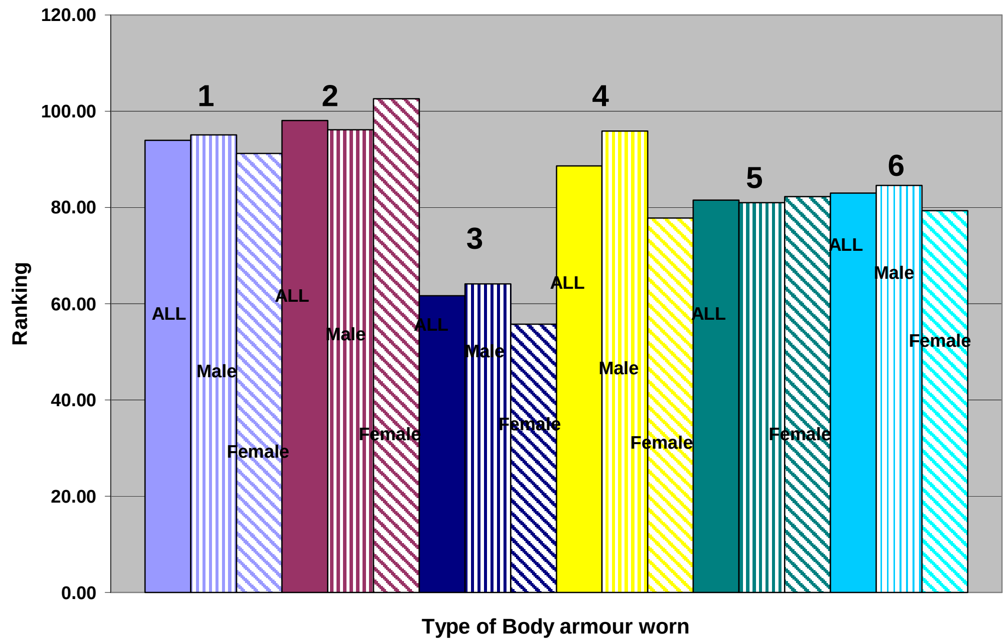

Figure 5. Ergonomic comparison of six different armour systems worn in trial

4.2 Activity Scoring

The average scoring of the volunteer group for each activity was found to be particularly useful in highlighting areas that the volunteers felt could be improved. Figure 6 illustrates a typical trial result and shows that although the particular armour sample performed well and did not chafe much (high score) they felt that the size, shape and fit could be better.

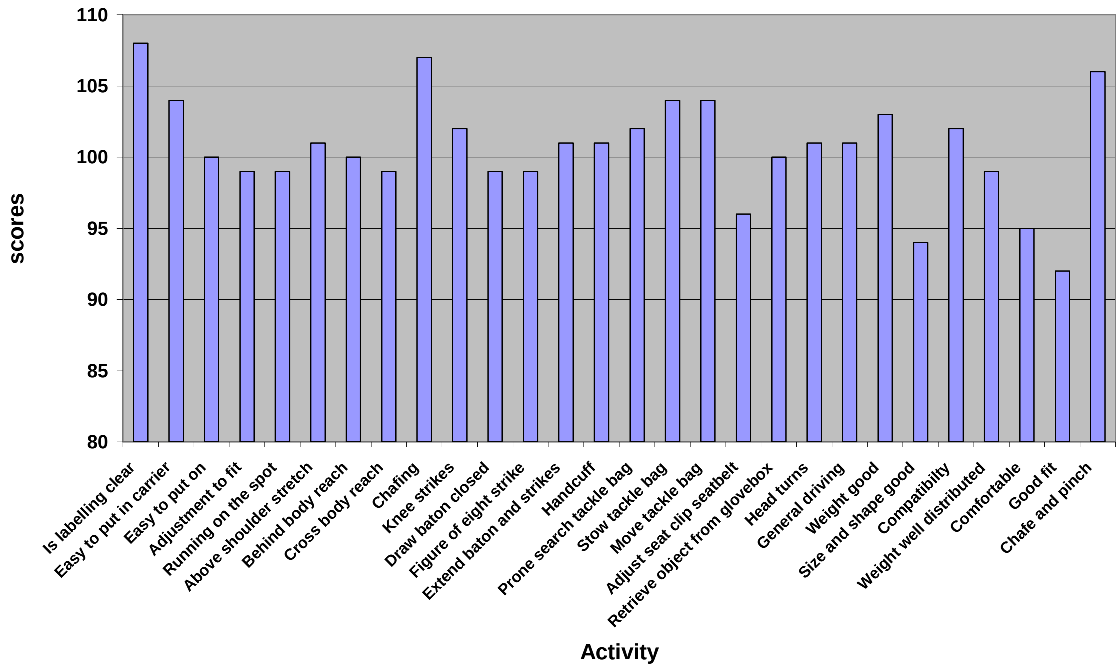

Figure 6. Average score for each activity for a typical trial armour

They had also found the cross body reach and fixing a seatbelt (also a type of cross body reach) more difficult than some of the other manoeuvres. Some armour designs had interfered with drawing their baton and handcuffs and the volunteers scored these low.

Generally the comments from the Police volunteers were that they liked the one page form filled in on the day of the trial whilst the differences were fresh in their minds. They preferred the one day approach rather than a long wearer trial as it gave them the opportunity to concentrate on the wearer trial away from their normal duties. They also felt the movements were relevant to their duties and therefore the trial was useful. The trials highlighted the specific points on an armour that could be improved such as adjustments to length of the armour to allow better access to equipment. Some volunteers reported that some designs became hot and uncomfortable to wear very quickly.

5. MILITARY TRIALS

The simple questionnaires and spreadsheet were modified (figure 7) for use in a further trial with Military Students at the Defence Academy College of Management and Technology (DA-DCMT). The aim of the trial is to demonstrate to the students the effect on manoeuvrability when the area of coverage and protection level is increased. The ergonomic effects of the different design features of armour are compared and useful feedback from students who have served in recent conflicts is collected.

Iremonger *et al* [9] in a previous study in 2006 had used four movements to assess the ergonomic effects of different body military armours these were: Leopard crawl, Fireman's lift and Casualty carry, climbing in and out of the back of a lorry and in and out of the lorry cab. The volunteers in that trial had commented that to be relevant to operational requirements the trials should involve some movements involving weapons handling. So the movements used in these trials were kneeling and aiming, lying prone and aiming with an SA80 weapon, climbing into the turret of a vehicle with a weapon, aiming and firing, moving around in the vehicle and a casualty carry using a 50Kg fireman's dummy.

ERGONOMICS CAPABILITY PRACTICAL

Male ☐ Female ☐

Complete the following tasks with two armours. Please score the level of difficulty, with

1=very difficult, 2=difficult, 3=some difficulty, 4 =easy

Armour type	**Kestrel**		**Osprey**		**French**		**US**		**Dutch**		**Danish**		**Norwegian**	

(Please tick one box for armour type worn)

	1	2	3	4
Ease of putting on/off				
Fit				
Flexibility				
Weight				
Comfort				
Kneeling and aiming				
Lying prone and getting up				
Head movements				
Fireman’s lift				
Aim/firing				
Aim/firing turret				
Getting in and out of a vehicle				

Figure 7. Typical Questionnaire for Military students

Approximately 150 students took part in the trials; each student chose two types of soft body armour fitted with ceramic plates to wear. These were either the UK Military Osprey or Kestrel armour or one of a selection of modern “Foreign” armour systems also fitted with ceramic plates. The systems were the US interceptor vest Mk1, French, Dutch, Danish and Norwegian designs all with side opening and adjustment. Helmets were also worn to compare the interaction of collars with the back of the helmet during the firing exercise. As the UK Military does not offer a personal fit merely a range of sizes, it was expected that the results from these armours would be more general and less specific than those from the Police trials. However, the purpose of the trial was to test the methodology to determine how much useful data could be obtained from a very short trial.

The area of coverage of military armour increases with the levels of protection offered. Kestrel armour was designed for “top cover” or sentry duty and it has no detachable parts it has a large area of coverage and offers a high degree of protection. Osprey also offers a high level of protection but has detachable arm protection and detachable collar options. The ‘Foreign’ armours offered similar levels of protection but all had optional groin protection and attached collars that were lower than the UK designs. The US interceptor was the only design to offer throat protection and the front panel of this design was cut away at the armholes to allow more arm movement in weapons aiming.

6. RESULTS

Figure 8 shows the results from the trial and as expected the larger area of coverage and higher level of protection offered by Kestrel meant movements were restricted and the ergonomic score for this armour was low. Collated comments from the students criticised the height of the collar at the back for interfering with the back of the helmet pushing it forward over the eyes when in the prone firing position. However many students who had worn Kestrel in operations liked the weight distribution and the side protection it offers when they had used it for 'top cover' in convoys.

The ergonomic scores for Osprey were better than those for Kestrel as the detachable arm protection and collars make movement easier. The height of the collars and their tendency to push the helmet forward when in the prone firing position was again criticised. Other comments were that they felt the armour was safer than its predecessor, ECBA. Fitting the armour usually needed two people as the velcro straps were difficult to align correctly by one person and that it was difficult to carry day sacks as the straps kept slipping off the shoulders of the armour. The ergonomic scores for the Norwegian and French type armours were similar and the students found these armours easier to put on but the collar interfering with the back of the helmet in the prone position was again a problem. The groin protectors were also felt to restrict movement and generally 'get in the way'.

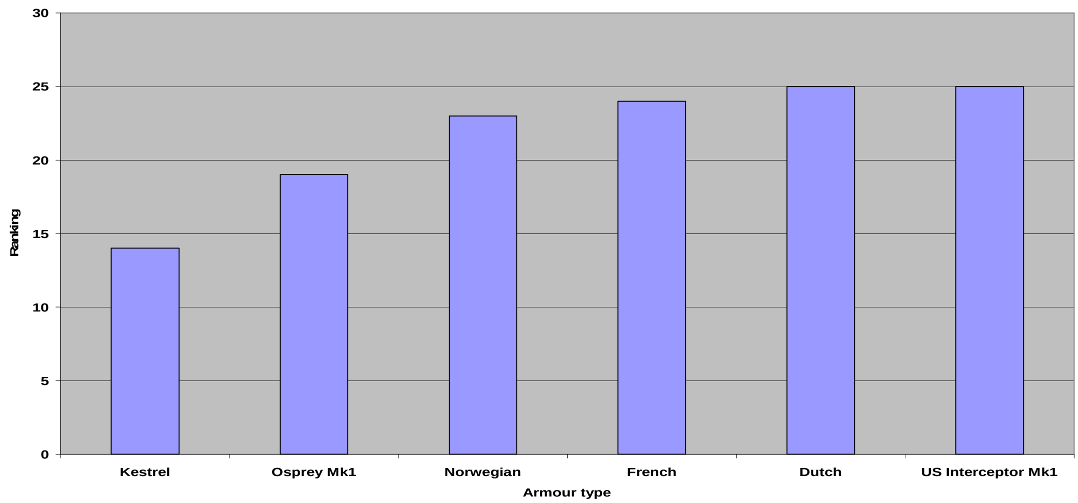

Figure 8. Ergonomic comparison of Military Body Armour systems

The Dutch and US armours had the highest scores due to fact they had no arm protection, offering much more freedom of movement. The groin protectors were felt to be awkward and the collars interfered with the back of the helmet. The trial proved that the questionnaires provided valid information that could be used to rank the ergonomics of the armours according to their area of coverage.

The military subjects were much more tolerant of discomfort than the Police subjects and concentrated on how the armour restricted access to their equipment and aiming their weapons. Collars which offer neck protection but interfere with the back of the helmet causing restriction when the head is moved to aim a weapon were particularly disliked. Protective ceramic plates that did not fit tightly and securely into the plate pockets moved about causing the weight distribution to be uneven also caused problems.

7. CONCLUSIONS

Both trials showed that simple well designed forms can provide relevant and useful data and that the data was useful as a design tool for modifying armour systems. The most successful movements for assessing Police armour were the twisting, bending and arm movements of upper torso which quickly highlighted ergonomic difficulties. Running on spot was excellent for highlighting possible chafing spots. For Military armour, aiming and firing manoeuvres were the best movements to isolate problems with armour interfering with other equipment. The simple ranking system was sufficient for these trials, however for the comparison of similar armour types, various tasks could be weighted in terms of relevance and a more complex ranking system developed. Because of the environment they have to operate in all subjects felt that the burden due to over heating was the most important factor to be overcome.

8. Acknowledgments

The author would like to acknowledge the contributions to this work made by Mr S Winslade, Mrs D Gair and Mrs Barnes-Warden from the UK Metropolitan Police and the military students at the Defence Academy, UK.

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